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ALTERNATIVE ENERGY SOURCES FOR FEDERAL AVIATION ADMINISTRATION FACILITIES

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AUGUST 1978

FINAL REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
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16. Abstract

A literature and industry/government search was made on alternative energy sources. This energy investigation effort concentrated on photovoltaics, wind, fuel cells and thermoelectric/thermionic generators that would produce electrical energy and appeared feasible for use at Federal Aviation Administration (FAA) facilities. As an aid to identify potential FAA facilities where it might be feasible to use an alternative energy system, two questionnaires were developed and distributed with the intent that a further in-depth investigation into a few selected sites would follow. Data from these questionnaires were received and tabulated.

As a result of this investigation, it was recommended that the FAA proceed to establish alternative energy demonstration sites in order to gain experience in the design, implementation, and operation of such systems. In addition it was recommended that due to the constantly changing and fast advancing nature of energy conversion systems, the FAA should expend some level of effort in continuing the literature/industry/government search initiated under this project in order to remain current on the subject. Also the FAA should establish a centralized data collection and tabulation point for energy requirements/consumption/cost data on a facility basis.

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METRIC CONVERSION FACTORS

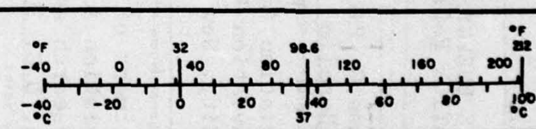
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

Acknowledgement is provided to Arthur R. Moss who drafted the section of this report on thermoelectric and thermionic energy, storage batteries, and appendix A; John B. Garry who drafted the section on fuel cell energy; and Harry T. Morgan who drafted the section on wind energy conversion systems.

Appreciation is expressed to Miss Dorothy Bulford, reference librarian at the National Aviation Facilities Experimental Center (NAFEC) Library, who provided valuable assistance in research and securing information on subjects related to alternative energy systems.

Appreciation is also expressed to the many individuals from industry and government who provided us with technical information and kindly took the time to discuss their activities with us.

A sincere thank you is in order to those Federal Aviation Administration (FAA) personnel who took the time and effort to complete the questionnaire thereby assisting in identifying potential candidate sites for alternative energy systems.

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GLOSSARY OF TERMS

ALS	Approach Lighting System
ARSR	Air Route Surveillance Radar
ARTCC	Air Route Traffic Control Center
ASR	Airport Surveillance Radar
ATCRB	Air Traffic Control Radar Beacon
ATCT	Air Traffic Control Tower
CERAP	Combined Center RAPCON
CS/T	Combined Station/Tower
DME	Distance Measuring Equipment
EFAS	Enroute Facility for Automation and Surveillance
FMAP	Fan Marker Approach
FPS	Fixed Pulse Radar Search Equipment
FSS	Flight Service Station
GS	Glide Slope
H	Non-Directional Radio Homing Beacon (<2kW)
HH	Non-Directional Radio Homing Beacon (>2kW)
HIALS	High Intensity Approach Lighting System
IFSS	International Flight Service Station
IFST	IFSS Transmitter
LCOT	UHF/VHF Link - Terminal
LMM	Compass Locator at Middle Marker
LOC	Localizer
LOM	Compass Locator at Outer Marker
LRCO	Limited Remote Communications Outlet

MALS	Medium Intensity Approach Lighting System
MALSR	Medium Intensity Lighting of Simplified
MB	Marker Beacon
MCOML	Marker/Compass Locator
MM	Middle Marker
MTR	Moving Target Reflector
NDB	Non-Directional Radio Beacon
OM	Outer Marker
PAR	Precision Approach Radar
RAPCON	Radar Approach Control (USAF)
RBC	Rotating Beam Ceilometer
RBDE	Radar Bright Display Equipment
RCAG	Remote Center Air/Ground Facility
RCO	Remote Communications Outlet
RAIL	Runway Alignment Indicator Lights
REIL	Runway End Identifier Lights
RMLR	Radar Microwave Link Repeater
RMLT	Radar Microwave Link Transmitter
RRH	Remote Reading Hygrothermometer
RTR	Remote Transmitter Receiver Facility
SFO	Single Frequency Outlet
SSALR	Simplified Short Approach Lighting System with RAIL
SSO	Self-Sustained Outlet
TACAN	UHF Tactical Air Navigational Aid
TACR	TACAN Located at VOR

TVOR	Low Power Terminal VOR
VASI	Visual Approach Slope Indicator
VOR	VHF OMNI-Directional Radio Range
VORTAC	Combined VOR and TACAN

INTRODUCTION

PURPOSE.

The purpose of this project was to conduct a state-of-the-art literature and industry/government search on alternative energy sources (photovoltaic, wind, fuel cells and thermoelectric/thermionic generators). A primary concern was to determine the feasibility of utilizing these alternative energy sources to supplement or replace conventional energy sources at Federal Aviation Administration (FAA) facilities.

BACKGROUND.

When conventional energy supplies cannot meet energy demands, an energy crisis usually arises. In the last 5 years this situation has manifested itself in the form of blackouts and brownouts; blackouts being a complete loss of power and brownouts being a reduction in the supplied power. The embargo on oil supplies from the Middle East countries resulted in curtailment of our energy supply and subsequently sharp increases in the price of oil occurred. Since oil is utilized to a large extent in the generation of energy, a corresponding significant increase in the price to the consumer resulted. FAA facilities, which number in the thousands, consume large amounts of energy. Energy requirements depend upon the type of facility and the equipment complement of the facility. For example, the Dallas/Fort Worth Air Route Traffic Control Center (ARTCC) requires over one megawatt (MW) of power; the Marker Beacon Station (MBS), however, may require only 26 watts (W). The FAA energy costs have risen rapidly in the last 5 years. If one assumes a projected yearly cost increase for energy of 10 to 15 percent, the current FAA energy bill will double every 5 to 7 years. As prices increase for conventional energy and decrease for alternative energy systems, it is expected that greater utilization of alternative energy sources will occur. Since this possibility is now approaching, it is highly appropriate that the FAA continue to monitor the development and application of alternative energy systems, to critically examine each type facility in order to assure the most efficient, cost effective, nationally beneficial approach to providing energy for the facility and to establish demonstration sites so that necessary experience may be gained and testing and evaluation of specific applications may be conducted.

In addition to the cost factor, there is a growing realization that the earth's natural energy resources are finite; that oil, natural gas, and coal will one day be exhausted. Coupled with this realization is the fact that energy requirements of the Nation and FAA will increase significantly during the next decade.

Another great concern of the Nation and the FAA is the pollution of our environment, which is attributable in part to the burning of coal and oil to produce energy. In contrast, solar photovoltaic and wind energy systems produce no pollution while fuel cells also offer significant pollution reduction potential.

Efforts were concentrated on alternative energy techniques that appeared feasible for use at FAA facilities. The following alternative energy systems were investigated and are discussed in this report: solar photovoltaic energy, wind energy, fuel cells, and thermoelectric/thermionic generators. In addition, since some type of energy storage medium is required for at least two of these systems, storage batteries were investigated along with such accessories as: inverters, converters, and voltage regulators. Geothermal, solar thermal, solar concentrators, ocean thermal gradients, solar powered heat engines, satellite solar power stations, etc., were not investigated.

With the assistance of the National Aviation Facilities Experimental Center (NAFEC) reference librarian, hundreds of abstracts were reviewed and requests were initiated to acquire those documents that were applicable to our field of interest. When available, these documents, including proceedings, papers, periodicals, and books were borrowed for further study. Visits were made to the United States (U.S.) Army Mobility Equipment Research and Development Command (MERADCOM) at Fort Belvoir, Virginia, to discuss photovoltaics and fuel cells; National Aeronautics and Space Administration (NASA), Lewis Research Center in Cleveland, Ohio, to discuss photovoltaics, wind energy systems, and fuel cells; Energy Research and Development Administration (ERDA) in Washington, D.C., to discuss photovoltaics and fuel cells; and Mitre Corporation in McLean, Virginia, to discuss their past activities in photovoltaics for ERDA. In the area of photovoltaic energy systems, visits were made to the following commercial industrial firms to view their facilities and to discuss the current development and manufacture of such systems: Solarex Corporation, Rockville, Maryland; Solar Power Corporation, North Billerica, Massachusetts; Mobil-Tyco Laboratories, Incorporated, Waltham, Massachusetts; and Solar Energy Systems, Incorporated, Newark, Delaware. Fuel cell development was discussed during visits to the following industrial firms: Exxon/Althom, Incorporated, New York City; Englehard Industries, Murray Hill, New Jersey; Energy Research Corporation, Danbury, Connecticut; United Technologies Corporation, South Windsor, Connecticut; General Electric Company, Wilmington, Massachusetts; and Griner Company, Waltham, Massachusetts. Thermoelectric generator development and manufacture was discussed during a visit to ITT Teledyne Incorporated, Baltimore, Maryland. A visit was also made to C and D Batteries, a division of Eltra Company, to discuss storage batteries.

Along with these visits, dozens of telephone contacts were made with other vendors involved in the development and/or manufacture of energy conversion systems and accessories.

A NAFEC alternative energy systems team was organized to accomplish this project. The men were assigned to specialty areas: photovoltaics, wind energy and batteries, fuel cells and thermoelectric/thermionics, FAA facilities and associated energy requirements, and cost considerations.

PHOTOVOLTAIC ENERGY

BACKGROUND.

Everyday the sun radiates energy to the earth at the rate of about one million times the entire electric power production capacity of the United States. For millions of years a very small percentage of this energy has been stored away in such a way as to provide us with fossil fuels. Today, it is quite evident that our consumption rate of fossil fuels is many times greater than nature's ability to create it. The stockpiles are steadily diminishing. Although we cannot easily duplicate the production process of fossil fuels, we can develop useable energy directly from the sun's radiation. With current technology, it is possible to convert to useful electrical energy somewhere in the order of 1 percent of the total incident solar photo energy available to the earth. This translates into an order of thousands of times our present energy consumption. Therefore, we can, with proper development, make use of photo energy conversion to supply our present and future energy needs by tapping this vast solar energy supply.

There are various methods for converting solar radiation into useable energy. However, photovoltaics, or direct conversion of radiant energy to electrical energy, appears to be the most promising and flexible method of obtaining useable energy from the sun.

As far back as a hundred years ago, it was known that certain substances generated an electrical current when exposed to light. But it wasn't until the early part of this century that a practical use appeared in the form of the light meter which is commonly used with cameras. With the development of the semiconductor industry in the 1950s, serious attempts were made to generate useable quantities of power. The space program provided the final push to make practical amounts of photovoltaic energy available.

The first silicon cells, although extremely expensive, were excellent in performance and very reliable. Of course, for the space program, the value of a cell or array of cells was measured in terms of energy per unit weight and not in cost. However, for earth applications, an entirely different set of values is being formulated since cost is very important and weight is relatively unimportant. New approaches to photovoltaic applications are being developed to make terrestrial arrays practical.

Since it was readily available, the first approach was to utilize silicon wafers, as used in the manufacture of transistors and other semiconductors. Although the circular configuration of wafer cells reduced the power-per-unit area, when compared to the custom-cut rectangular space-type cells, the cost reduction was in the order of two magnitudes. For terrestrial applications, the increased array area presents no major problem, at least in the small sizes in use. Terrestrial applications have introduced several other impediments in the form of reduced insolation (the rate of delivery of all direct solar energy per unit of horizontal surface) higher ambient temperatures, and corrosive atmospheres. Each of these tends, to reduce cell output from the theoretical maximum.

Insolation is an extremely variable parameter at the earth's surface, when compared to the stable conditions of space. Figure 1 shows that on a clear day approximately 82 percent of the total radiated solar energy could reach the surface of the earth, the remainder being reflected back into space and absorbed in the atmosphere. On an overcast day, approximately 47 percent could reach the surface of the earth. However, under very severe cloud cover, the surface insolation may be reduced to a mere 1 percent. The amount of energy received at the earth's surface at noon at sea level on a clear day is approximately 1.4 killowatts per square meter (kW/m^2). Assuming a 10 percent conversion efficiency of photovoltaic cells, about 140 W would be converted.

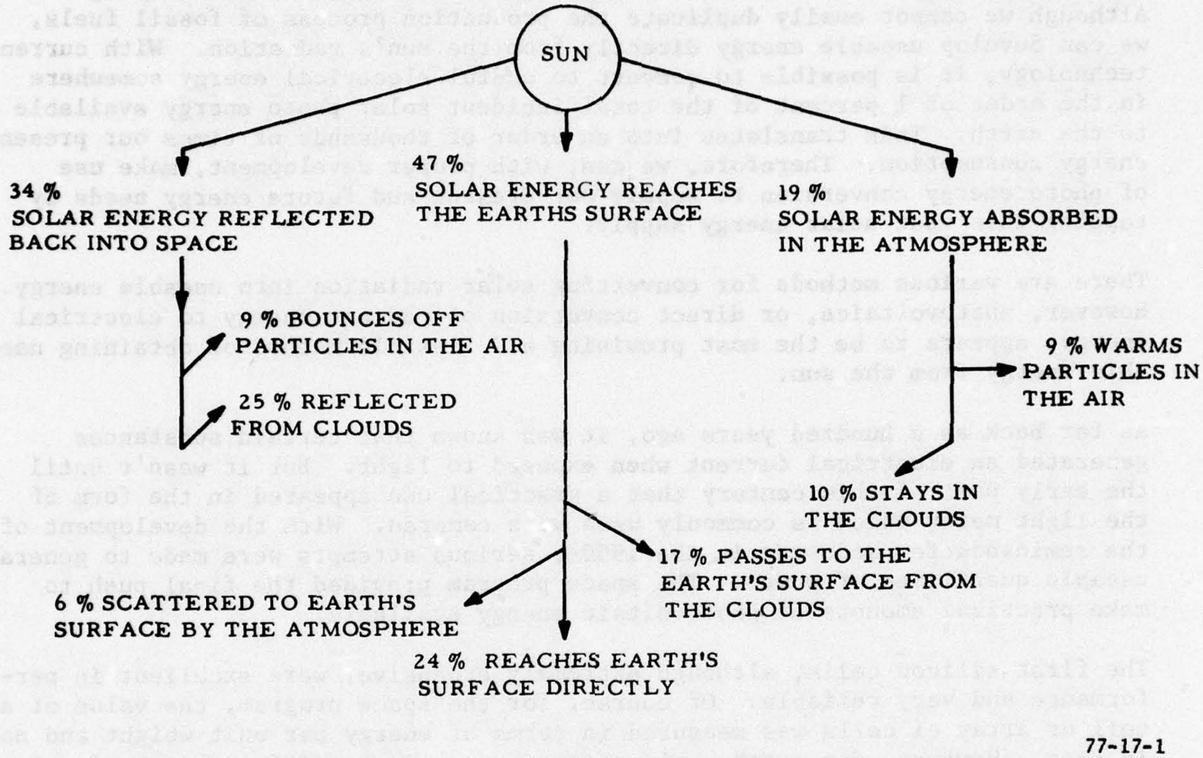

FIGURE 1. LOSS OF SOLAR ENERGY RADIATION THROUGH THE ATMOSPHERE

The diurnal cycle plays an important part in the instantaneous insolation. From sunrise to sunset the insolation follows a one-half sinusoidal wave from zero to maximum and back to zero. Figure 2 shows that the amount of insolation is also affected by both the latitude and the season. In general, in the northern hemisphere, the greatest daily insolation total occurs around the summer solstice. In addition to these fixed variables, there are other local and almost unpredictable variables, such as: the weather, fog, smog, and pollution. Insolation maps have been drawn for the country showing average values by the month and year. An example of such a map is shown in figure 3. From this data, it is found that the southwest generally has the highest insolation in the country with the Great Lakes and Northeast regions having the lowest.

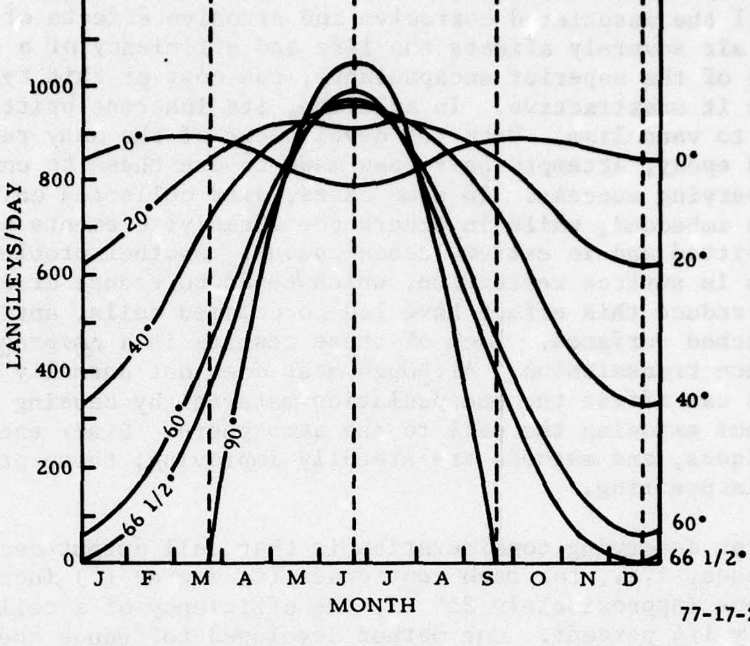

FIGURE 2. ANNUAL VARIATION IN DAILY ISOLATION AT SELECTED LATITUDES IN THE NORTHERN HEMISPHERE

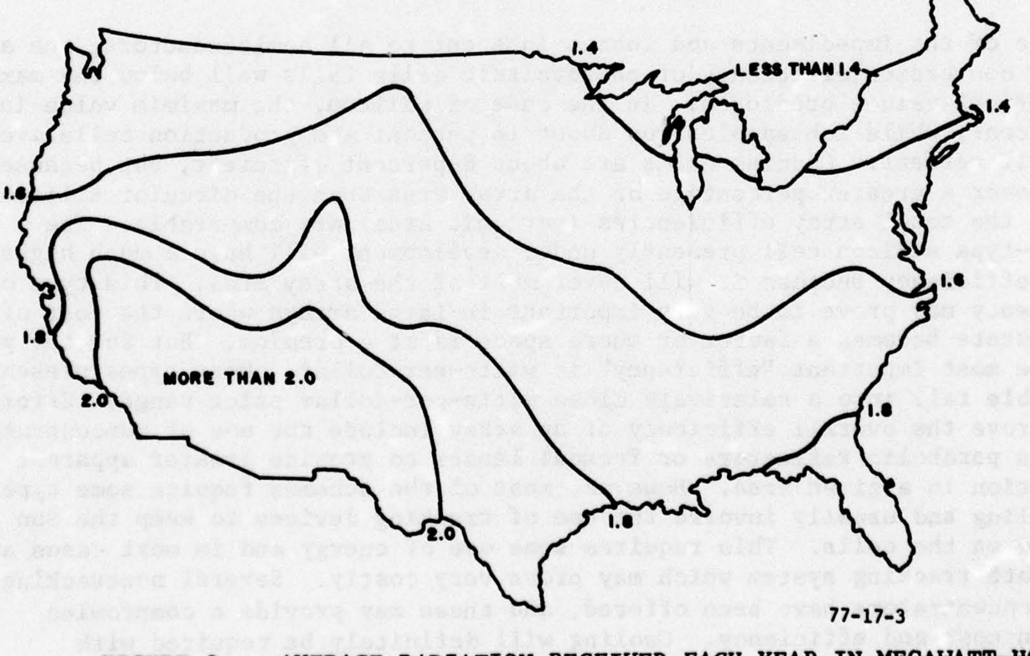

FIGURE 3. AVERAGE RADIATION RECEIVED EACH YEAR IN MEGAWATT-HOURS/SQUARE METER

Reduced output and failure can occur unless a photovoltaic cell is enclosed within some type of protective encapsulation material. Exposure to the atmosphere and all the associated corrosive and errosive effects of dirt and pollutants in the air severely affects the life and efficiency of a cell. Although glass is one of the superior encapsulants, the cost of this type material generally makes it unattractive. In addition, its inherent brittleness makes it susceptible to vandalism. With the development of the many resins such as acrylics and epoxy, attempts have been made to use these to encapsulate the cells with varying success. In some cases, dirt collected on the surface actually becomes imbedded, while in others the abrasive elements erode the surface leaving it pitted and in extreme cases opaque. Another problem common to all encapsulants is surface reflection, which tends to reduce array output. Various attempts to reduce this effect have led to colored cells, antireflective coatings, and etched surfaces. Each of these results in a compromise since they tend to reduce transmission. Although heat does not normally damage a cell, extreme heat can affect the encapsulation material by causing it to opaque or separate, thus exposing the cell to the atmosphere. Since encapsulation materials, techniques, and methods are steadily improving; these problems are gradually disappearing.

Another factor deserving consideration is that cell output decreases as temperature increases, i.e., for each centigrade (C) degree (°) increase above standard conditions (approximately 25° C), the efficiency of a cell is reduced approximately 1/4 percent. One method developed to reduce the effect of this is to water cool the array and then use the heated water for heating and cooling purposes. In addition to maintaining the cell efficiency, this also improves the total energy output of the system.

Because of the impediments and losses inherent to all semiconductors, the actual energy conversion efficiency of photovoltaic cells falls well below the maximum theoretical values predicted. In the case of silicon, the maximim value is 22 percent, while lab samples run about 16 percent and production cells average about 12 percent. Cadmium cells are about 8-percent efficient, but because they cover a greater percentage of the array area than the circular silicon cells, the total array efficiencies (per unit area) are comparable. The ribbon-type silicon cell presently under development will have a much higher array efficiency because it will cover most of the array area. This type of efficiency may prove to be very important in large arrays where the cost of real estate becomes a factor or where space is at a premium. But for the present the most important "efficiency" is watts-per-dollar. Most types presently available fall into a relatively close watts-per-dollar price range. Efforts to improve the overall efficiency of an array include the use of concentrators such as parabolic reflectors or fresnal lenses to provide greater apparent insolation in a given area. However, most of the schemes require some type of cooling and usually involve the use of tracking devices to keep the sun focused on the cells. This requires some use of energy and in most cases an elaborate tracking system which may prove very costly. Several nontracking-type concentrators have been offered, and these may provide a compromise between cost and efficiency. Cooling will definitely be required with these systems because of the greatly increased concentration of heat.

Due to the circadian cycle of sunlight, in which there is none at night, no energy can be supplied during this time unless it is stored. Although "daytime only" devices may be used for FAA applications, these are not always practical. Despite the fact that many varied schemes of storage have been and are being advanced for present applications, the field seems to narrow down to storage batteries. This fact must be kept in mind whenever considering any usage of photovoltaics as a source of continuous energy.

THEORY.

At the present time, most photovoltaic converters are semiconductor-type diodes. The most common type is the silicon wafer which is simply a large surface silicon diode with transparent encapsulation to permit the entrance of solar radiation. In the absence of radiation, the cell behaves as a standard silicon diode. However, when a photon available from solar radiation strikes an electron in the silicon crystal, the photon energy is transfered to the electron causing it to move from its orbit. As a result, an electric field is established with a potential difference being generated between the p-n junction of about 0.5 volts (V). If a load is connected across this potential, a current will flow. Under normal loading, the voltage will remain relatively constant while the current will vary directly with the radiation intensity. Individual cells currently being manufactured can produce at noon on a clear day, up to 2 amps, depending on the size of the cell.

TECHNOLOGY

At present, there are three major areas of development in photovoltaic cell manufacturing processes, two of which are associated with the use of silicon and the other with cadmium sulfide. None of these have reached mass production, and even though a consumer product is being produced, these manufacturing processes are still considered to be in the developmental stage.

Of the three major areas of development, the first is based upon using silicon wafers up to 10 centimeters (cm) in diameter with a thickness of .025 to .05 cm. These are sliced from cylindrical ingots of pure silicon which is grown by the Czochralski Method. This method of growing silicon crystals is based on dipping a rotating seed crystal into a crucible of molten silicon and then slowly withdrawing it. The result is a large cylindrical crystal 3 or 4 inches in diameter and several feet long. If an appropriate amount of boron is first added to the melt, the crystal is uniformly doped with boron. In making a silicon cell from such a crystal, the crystal is cut into thin wafers; a process in which a substantial portion of the crystal is lost as sawdust. One surface of each wafer, which is of p-type silicon, is converted into a layer of n-type silicon by being exposed to phosphorus at a temperature high enough for the phosphorus atoms to diffuse a short distance into it, thus forming the p-n junction. The surfaces are metalized by masking to provide electrical contacts to the cell. Figure 4 illustrates the completed cell. The edges of the cells are then hand polished to remove any burrs and a copper ribbon wire is soldered to the cell metalization network to provide the intercell connection. The cells are then laid out on a rigid panel, usually made of a fiberglass material, and the ribbon leads are soldered together to

provide the proper series/parallel connections which determine the output. The cells are then encapsulated and secured to the panel by means of a transparent silicone rubber or other similar encapsulation material. After final adjustments, the panel is tested and rated in actual sunlight by comparing it against a standard. Although batch processing is used to some extent in the fabrication of the cells and panels, little automation is currently available. The high initial cost of the silicon ingots and the extent of hand labor involved, results in high costs. However, it is expected that appreciable cost reduction will result when mass production becomes a reality.

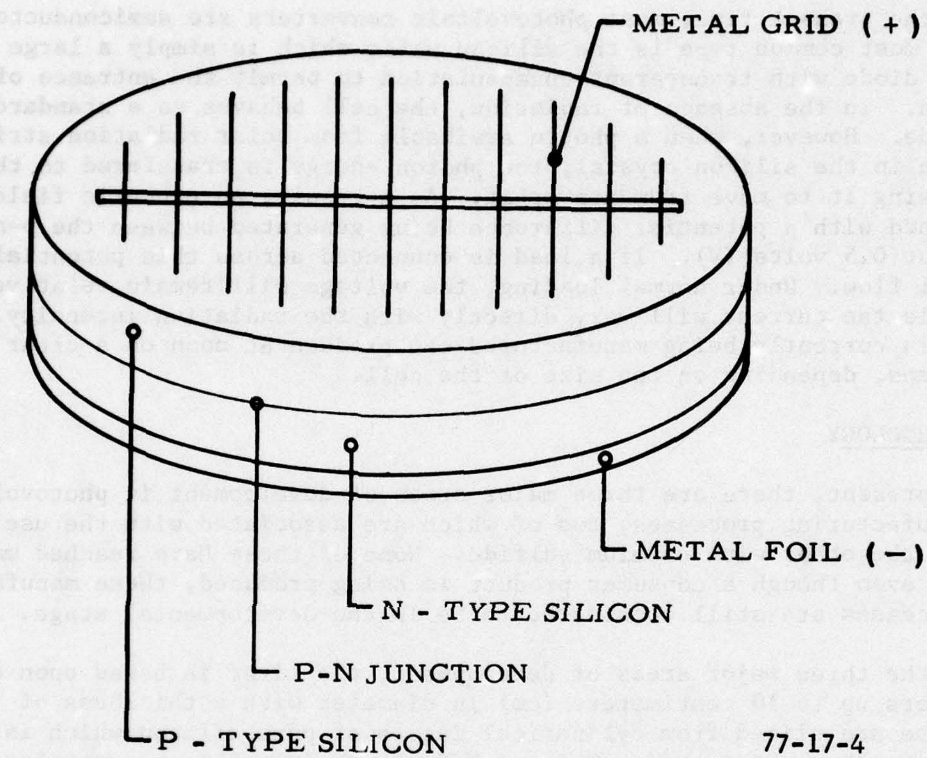

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FIGURE 4. SILICON PHOTOVOLTAIC CELL (WAFER TYPE)

The second major development is the Edge-Defined Film-Fed Growth (EFG) technique. This technique consists of using a crucible of molten silicon the same as with Czochralski Method but instead of growing ingots, continuous silicon ribbons are grown. By using the capillary action principle, the molten silicon with a trace of boron to make it a p-type conductor is drawn inside the narrow channel of a carbon graphite die, which has been seeded with silicon crystals to start the action. As it is pulled upward, a continuous ribbon is grown, the dimensions of which are determined by the die. Next, one surface of the ribbon is converted into a layer of n-type silicon, in much the same manner as the silicon wafers, to form the p-n junction. The metalized grid is added, and the result is a ribbon which is suitable to cut into appropriate sections and form solar photovoltaic cells. Raw material usage is

optimized with this process, since there is no cutting operation required as is the case in fabricating silicon wafers. According to Mobil-Tyco Solar Energy Corporation, the developer of the EFG technique, only 4.5 kilograms per kilowatt of silicon is required, which is about 1/7 the amount of silicon required for fabricating silicon wafers. This EFG technique, which is more commonly referred to as the ribbon technique, promises cost reductions of at least one order of magnitude when finally placed into production. At the present time, this technique is still in the research and development (R and D) stage with estimates from 1 to 8 years before it actually reaches production, dependent mainly upon market demand. Tyco reports growing ribbons up to 50 millimeters (mm) wide and 25 meters (m) long from a single die per crucible. To be economical, Tyco feels that ribbons 50-150 mm wide would have to be grown from six dies simultaneously from a single crucible and in much greater lengths. It should be pointed out that the exact status of this work is uncertain due to the proprietary nature of the work.

The last major development is a thin film technique utilizing cadmium sulfide/copper sulfide rather than silicon. The first step in the fabrication of cadmium sulfide cells is to vacuum deposit a thin film of n-type cadmium sulfide on a porcelinated metal substrate. Then a very thin layer of p-type copper sulfide is deposited on top of cadmium sulfide using an ion-exchange reaction. A metal grid electrode is then placed on top under very high pressure. The current standard design is to fabricate a module which consists of a group of cell segments. These modules are nominally 8-inches square. A completed module is illustrated in figure 5. These modules are assembled in the proper series/parallel configuration to provide the desired output and then laid on a rigid panel. Glass is then laminated over the whole sandwich and hermetically sealed. This process was developed by Solar Energy Systems (SES), Incorporated. A pilot production plant is currently in use while a second larger pilot assembly line is being set up and scheduled for use in 1978. Plans and groundwork have been formulated for a true production plant to be established in the near future. Of the facilities visited, this is the only one showing real evidence of a large yield production capability in the near future.

INSTALLATION. A basic solar power system would consist of an array of cells, a blocking diode, an optional voltage regulator, and a storage device (at present the storage device would be a battery). The array would consist of a number of photovoltaic cells mounted on a panel and connected in series and/or parallel to obtain the required output. Additional panels could also be wired in series and/or parallel to increase the output to the desired power level. The storage battery would be used to store energy for off-peak usage, severly cloudy days, and at night. Since during the absence of solar radiation, the photovoltaic cells would be forward-biased by the battery voltage, a blocking diode should be used to prevent discharging the battery through the cells. A voltage regulator would be desirable to prevent overcharging of the storage battery. This basic system, if properly sized, could be used to power any direct current system. However, an inverter could be added to the system if an alternating current output is desired.

The location and angle of tilt of the array in relation to the surface of the earth are the important elements in the installation. The array should be located so that an optimum amount of direct solar radiation will strike it from sunrise to sunset during both summer and winter with no shading. Since the arrays are modularly constructed, location is quite flexible. The angle of tilt of the array is critical if the maximum year round energy availability is to be achieved.

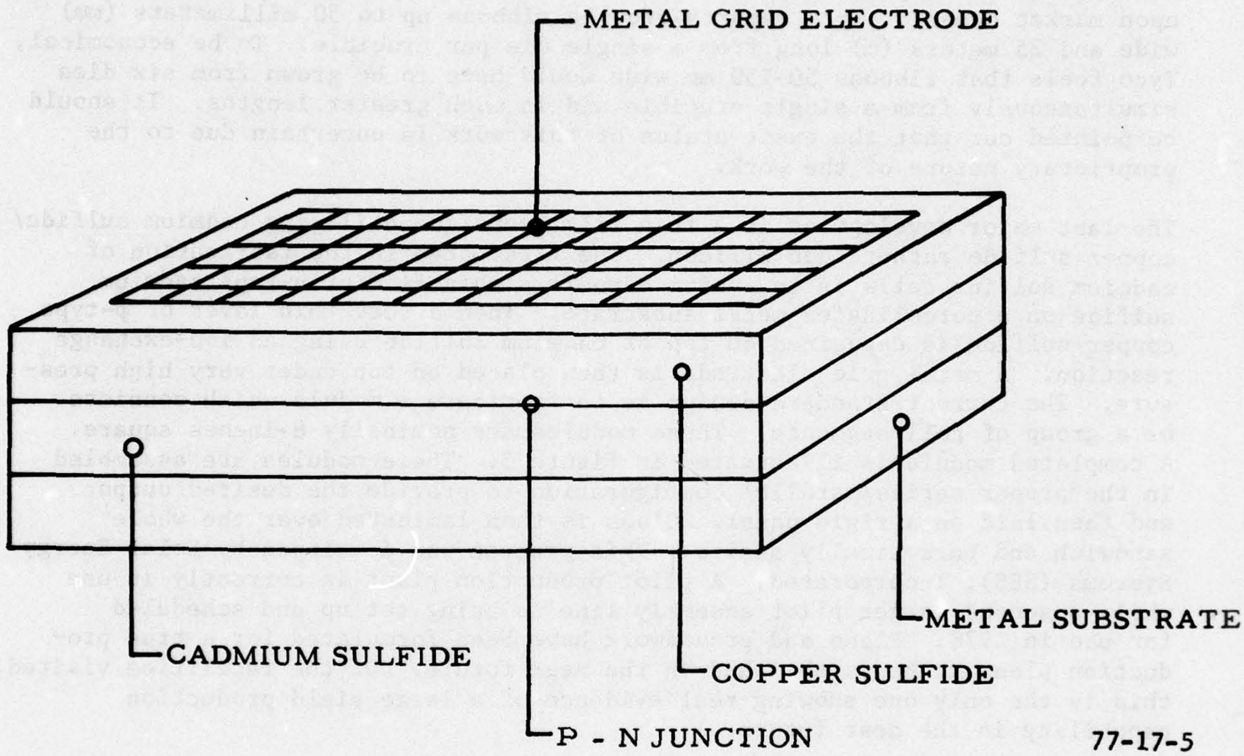

FIGURE 5. CADMIUM SULFIDE PHOTOVOLTAIC CELL

In order to determine the optimum fixed angle of tilt for the array, consideration must usually be given to the worst case conditions, which in the northern hemisphere are the winter months. Although determination of the proper tilt angle must be done on a site by site basis; generally, the angle would be 10 to 15 degrees more than the latitude of the location. Of course, in the northern hemisphere, the array should be oriented toward the south.

The storage battery and voltage regulator are usually collocated because of their close association and are normally placed in a shelter for weather protection. In large installations, the weight of the batteries may be a

factor to consider. An important factor in analyzing the location of the storage batteries is to minimize the distance from the array in order to reduce power loss in the connecting cable and to use as large a cable size as practical. If an inverter is used, it should be located as close to the storage battery as possible for the same reason.

An example of the use of photovoltaic power systems is shown in figures 6 and 7. Figure 6 is a microwave repeater station with a power requirement of less than 75 W, while figure 7 is an airport marker beacon station with a power requirement of approximately 26 W.

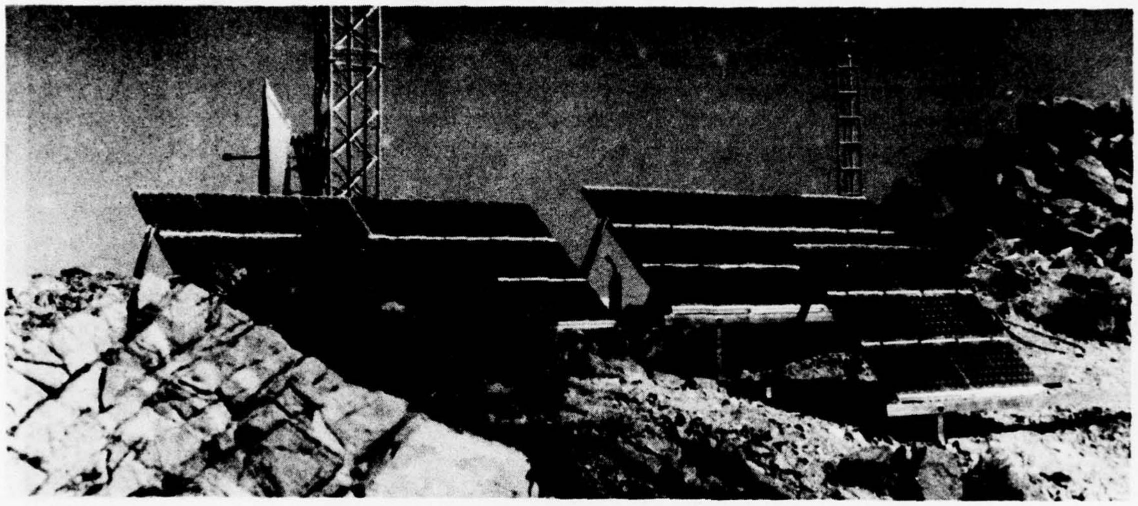

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FIGURE 6. MICROWAVE REPEATER SYSTEM

SUMMARY.

Photovoltaics are technically feasible today as a source of alternative power. Although their cost-per-watt is still high, it is projected to be reduced appreciably by 1985. For FAA applications, they could be used cost effectively in remote or isolated sites where conventional or other power sources prove to be expensive to install, operate, and maintain. Prices are expected to drop as the market develops and production methods improve. Where continuous power is required, energy storage is a necessary adjunct, since insolation is a variable factor. If an alternative to the storage cell is not developed, energy storage may be the limiting factor in any final cost reduction. Also reliability of terrestrial arrays has not been extensively demonstrated and literature in this area is limited.

77-17-7

FIGURE 7. AIRPORT MARKER BEACON STATION

Most of the problems encountered in the use of solar array systems arise from the fact that the terrestial photovoltaic industry is just entering the application stage. Users, as well as vendors, have limited application experience. Since potential applications for photovoltaics definitely exists within the FAA, it seems logical and reasonable that the FAA should proceed to gain further knowledge and experience through the establishment of small demonstration or pilot installations operated under controlled conditions. With this experience and eventual price reductions, the FAA will have flexibility in the application of alternative energy systems and in the selection of site installations.

WIND ENERGY

BACKGROUND.

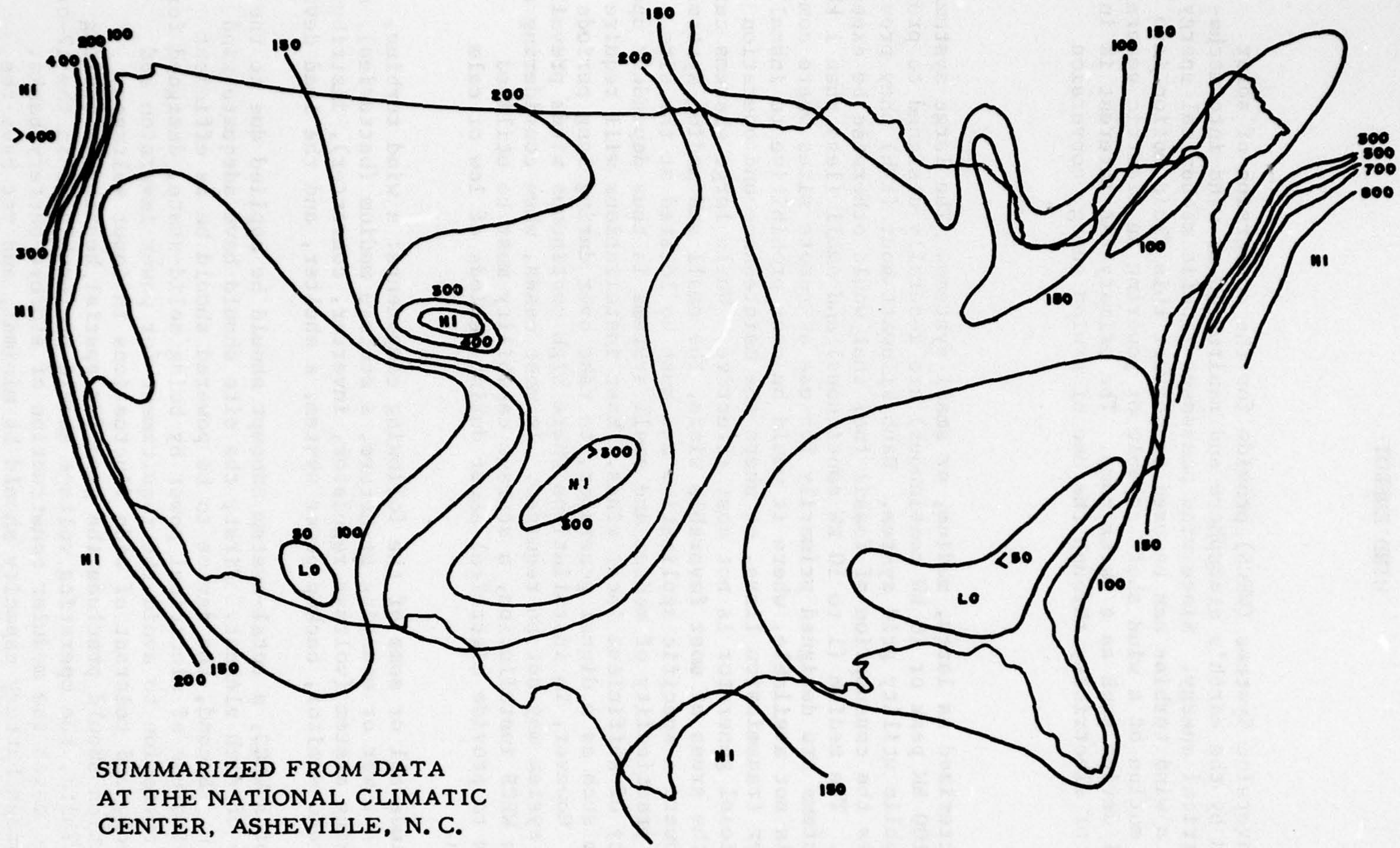
Wind Energy Conversion Systems (WECS) provide for the conversion of solar energy captured by the earth's atmosphere and manifested as wind into mechanical and electrical energy. Since wind possesses kinetic mechanical energy of fluid flow, a wind turbine can be used to convert this fluid motion into the rotational motion of a wind shaft capable of powering an electric generator or a mechanical device such as a water pump. The primary FAA interest is in the generation of electricity through the use of a wind energy conversion system.

THEORY.

WECS are characterized as large, medium, or small systems. The large systems (greater than 100 kW peak or 10 kW continuous) are generally designed to provide power to the public utility grid system. Each kilowatt hour (kWh) they provide directly reduces the consumption of fossil fuel that would otherwise be expanded by the utility. The medium (1 to 10 kW continuous) and small (less than 1 kW continuous) systems are designed primarily for use at remote sites where commercial power is not available, where it would be cost prohibitive to install commercial power transmission lines, or where the maintenance and operation of a standby diesel generator is not cost effective. While large systems can be located in the areas of most favorable winds, the small and medium systems are directed toward a specific application and must be located at the site of usage. The practicality of medium and small systems is thus dependent upon the availability of sufficient local winds. Most installations will require a backup system such as a diesel generator, to take over during long periods of calm winds. However, in installations where high continuous winds prevail, a backup power system may not be required. In most cases, when considering a small to medium WECS installation, a storage capability must be utilized with the system to provide electrical power during periods of low or calm wind conditions.

A WECS may include all or some of the following components: a wind turbine, an alternator, a tower or mounting structure, a storage medium (batteries), a power conditioning system (voltage regulator, inverter, converter), distribution, controls and monitor, backup power system, a shelter, and the load device.

In the design of a WECS, a total-system concept should be applied due to the interdependence of each element. First, the site should have adequate wind energy available. Second, the device to be powered should be as efficient as possible in the use of electrical power by being solid-state, designed for direct-current operation to avoid the requirement for power inversion and frequency control, and tolerant of wide fluctuations in input voltages. Component selection should preclude the need for special heating or cooling requirements. Third, the operating voltage should preferably be in the 12-or 24-volt range to match the modular construction of storage battery banks. Fourth, the storage battery capacity should be minimal, and yet have the capability of sustaining uninterrupted operations for the longest period of



SUMMARIZED FROM DATA
AT THE NATIONAL CLIMATIC
CENTER, ASHEVILLE, N. C.

77-17-8

FIGURE 8. ANNUAL AVERAGE AVAILABLE WIND POWER IN WATTS/SQUARE METER

forecasted calm winds; this can be achieved by effective specification of storage to backup energy ratios. Fifth, the maintenance goal should be set for an annual cycle, while the system service life goal should in the 20-year range.

Wind is the fuel for a WECS. Where available, it is free, consumes no earth resource, and is non-polluting. Figure 8 is a map of the United States with lines of equal wind velocities averaged over several years. It shows that the greatest winds are generally available in the Texas panhandle area, in the Colorado area, and off the Atlantic and Pacific coasts.

Wind is a by-product of solar energy transferred to the earth's atmosphere. It is a component of what man generally refers to as weather. Meteorology, the science of weather, reveals that like many natural resources, wind is both geographical and seasonal in character. Wind energy follows natural laws that provide a direct relationship between energy output (E) of a given installation, the product of fluid density (p), the cross sectional area of flow (A), and the cube of velocity of flow (v). This can be expressed as $E \propto pAv^3$. At a given installation, wind velocity is the only variable factor. Figure 9 is a typical installation showing how power output varies with wind velocity and the physical limitations of the wind turbine.

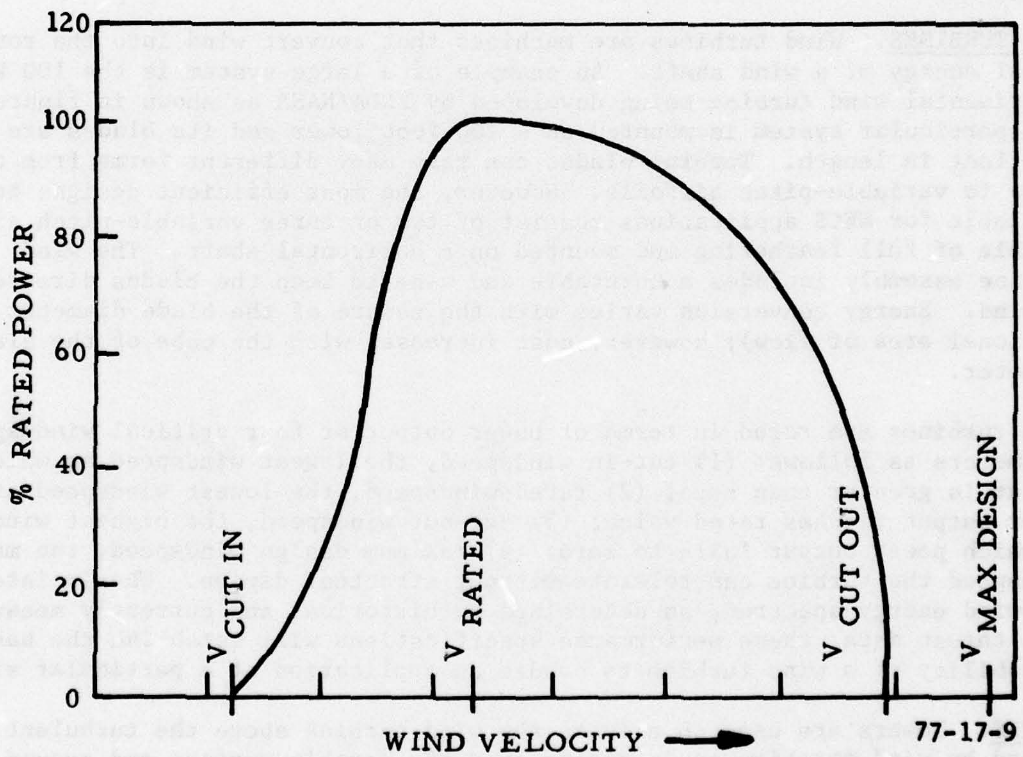


FIGURE 9. TYPICAL POWER OUTPUT VERSUS WIND VELOCITY

Units of wind power take on a disproportionate rank corresponding to their velocities. For example, using a 10 mile-per-hour (mph) flow as a base, a 30-mph flow theoretically has 27 times the energy content. A steady 10-mph wind flow over a 2-hour period has the same average wind velocity as a steady 20-mph flow for 1 hour followed by a calm period for 1 hour. However, the energy produced within these 2-hour periods is four times greater in the latter case due to the cube power law. This means it is preferable to have a 20-mph wind for 1 hour than a 10-mph wind for 2 hours. Thus, in site evaluation, the average wind velocity cannot be simply related to average energy output. The energy output must be calculated by employing sampling techniques that integrate both wind velocity and time duration. Special equipment known as Wind Spectrum Analyzers and Wind Energy Monitors are commercially available for this purpose.

Average energy output of a wind turbine must at least be equal to the average energy consumed by the load device at the site or the storage medium will gradually be depleted. This means that if no backup power source is installed, the storage capacity must exceed the longest forecasted period of zero wind turbine output. Practically, this dictates that the electrical load be a small fraction of the rated output of the wind turbine. Typically, this would be in the range of 0.1 to 0.2 of the rated output.

TECHNOLOGY.

WIND TURBINES. Wind turbines are machines that convert wind into the rotational energy of a wind shaft. An example of a large system is the 100 kW experimental wind turbine being developed by ERDA/NASA as shown in figure 10. This particular system is mounted on a 100-foot tower and its blades are each 62.5 feet in length. Turbine blades can take many different forms from cloth sails to variable-pitch airfoils. However, the most efficient designs currently available for WECS applications consist of two or three variable-pitch airfoils capable of full feathering and mounted on a horizontal shaft. The wind turbine assembly includes a turntable and vane to keep the blades directed into to wind. Energy conversion varies with the square of the blade diameter (cross sectional area of flow); however, cost increases with the cube of the blade diameter.

Wind turbines are rated in terms of power output at four critical wind speed parameters as follows: (1) cut-in windspeed, the lowest windspeed at which power output is greater than zero; (2) rated windspeed, the lowest windspeed at which power output reaches rated value; (3) cut-out windspeed, the highest windspeed at which power output falls to zero; (4) maximum design windspeed, the maximum windspeed the turbine can tolerate without structual damage. When related to the wind energy spectrum, as determined by historical and currently measured wind thrust data, these performance specifications will establish the basic suitability of a wind turbine to handle an application at a particular site.

TOWERS. Towers are used to elevate the wind turbine above the turbulent flow caused by wind friction as it passes over the earth's surface and around obstructions. Turbulent flow, if permitted, will fatigue-fail turbine blades; in severe cases, blade contact with the tower can occur. Although investigations are currently underway into advanced blade designs that are less susceptable to damage from winds of high velocity, this work is still considered to be in the development stage.

FIGURE 10. ERDA/NASA 100 kW EXPERIMENTAL WIND TURBINE

As shown in figure 11, wind velocity increases with height. Since the power output increases with the cube of wind velocity, a compromise can be made between tower height and turbine rating. Provisions must be made in the tower structural design for strength to withstand storm winds.

ELECTRICAL GENERATORS. The electrical generators driven by the wind turbines usually take the form of alternators to avoid the short life and maintenance required on brushes that are utilized in direct-current generators. Alternators are mounted on towers and are either direct or gear driven by the turbine shaft. In wind technology, rotational velocities in the 100-800 rpm range are normal and a service life in the 100,000-hour range is desired. This dictates that wind turbine alternators be massive, atypical, and usually expensive.

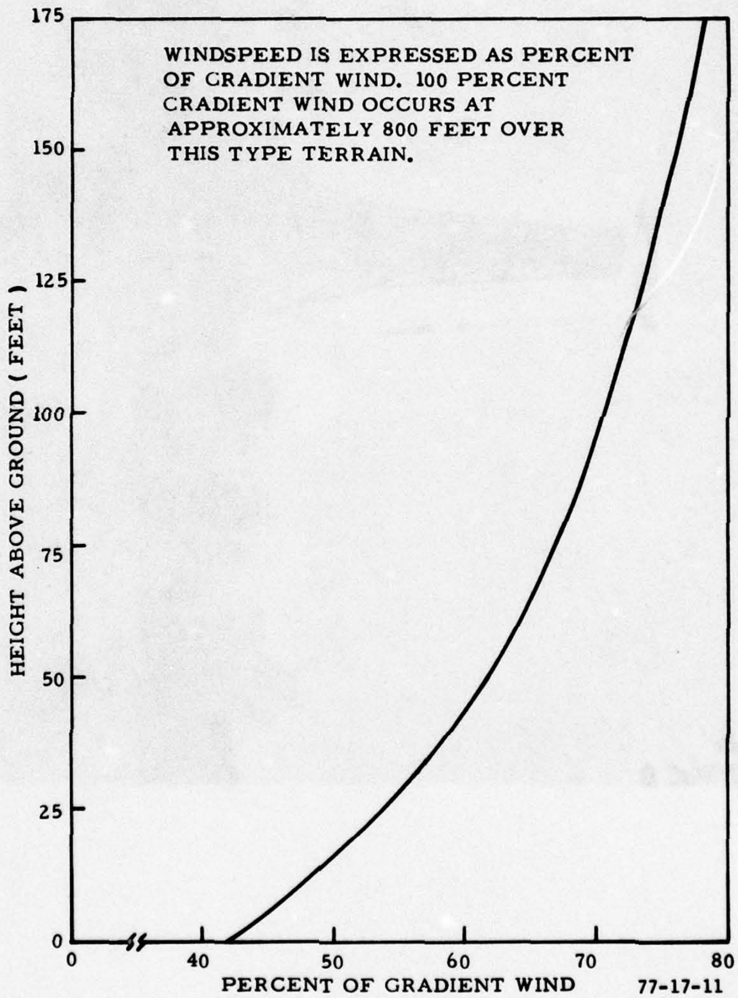


FIGURE 11. VARIATION OF WINDSPEED WITH HEIGHT ABOVE THE GROUND FOR FLAT TERRAIN OR WATER

ENERGY STORAGE. A storage medium is required to average out the fluctuations in power generation due to the ever varying magnitude of wind energy and to carry the load during the periods of calm winds. Although exotic means of energy storage are under development, currently the only practical method is the use of industrial type, deep discharge, lead-acid storage cells. This storage medium is the direct supplier of energy to the load, with either the wind turbine alternator or backup system (if used) acting as the replenisher. Judicious tradeoffs can be made between wind turbine ratings, storage capacity, and the use of a backup power system.

BACK-UP POWER SYSTEMS. Backup systems are normally fossil-fueled, engine-driven power plants, for reasons of simplicity and reliability. Generally, it is cost effective to incorporate a backup system to gain the economies of reduced wind turbine ratings and battery storage requirments. If the average wind turbine energy output is less than the average load requirement, some type of supplemental backup system is mandatory.

POWER CONDITIONING. Power conditioning is necessary to rectify and regulate the output of the wind turbine and diesel alternators. If the load requires alternating current (a.c.), inverters to transform the battery energy to this form will be required. Further requirements for frequency and wave form control may also be necessary.

DISTRIBUTION, CONTROLS, AND MONITORS. Since the distribution lines will be carrying direct current (d.c.) of high amperage, they should be of sufficient size and length to avoid excessive line losses and costs.

A variety of controls and monitors will be necessary. There must be some type of wind-force sensor to protect the turbine blades in hurricane force winds. Other wind and battery sensors must be provided to determine when to switch the backup system on and off. Warnings of impending maintenance problems or system outage should be provided.

SHELTERS. Shelters must be provided at the site for the battery storage bank, the power conditioning equipment, the control and monitoring equipment, and the backup power system.

CANDIDATE SITES. Candidate sites for small to medium WECS should possess a combination of the following characteristics: (1) no reliable commercial power or the cost to provide it is excessive, (2) site is unattended for long periods of time, (3) environment is hostile or primitive. (4) limited access or severe weather, (5) site requires minimal security, (6) wind is determined to be cost effective compared to other energy systems, and (7) availability of adequate winds.

The decision to employ a wind turbine at a specific site should be preceded by an economic and technical analysis. After the analysis has been completed, the wind turbine can be properly selected, the capacity of the storage battery bank determined, the need for a backup power source decided, and the wind turbine tower requirements specified.

In the National Airspace System (NAS) there are believed to be applications that would lend themselves to the advantages provided by wind energy. Further study is required to determine what specific sites and facilities would be suitable candidates. However, one known device that seems to meet the criteria is the Instrument Landing System Outer Marker Beacon. It is low powered (approximately 26 W continuous), solid-state, 12 or 24 V d.c. powered, and designed for use at remote sites.

ROLE OF ERDA. The Energy Research and Development Administration has contracted with Rockwell International Corporation to operate an ERDA wind turbine test facility at Rocky Flats, Colorado. This effort will be on-going for the next several years. Procurement of different wind turbines is in process with sizes ranging from 200 W to 100 kW. This facility will be the principal government test and evaluation site to monitor and foster small wind turbine progress. Contact has been made with both ERDA, Washington and ERDA, Rocky Flats, requesting placement on the distribution list to receive data and reports as they are issued.

SUMMARY.

Wind is a proven alternative energy technique which, if applied under an energy management philosophy that recognizes both its limitations and special advantages, can be employed at its present state of development at remote FAA sites requiring low to medium power.

WECS are commercially available and have the advantage of being nonpolluting and requiring no furnished fossil fuel, except for that which might be necessary to power a backup system.

Because of the many applications within NAS, where on-site energy generation is required, the FAA is in a unique position to both foster and profit from the reemergence of wind energy systems brought up to 20th century standards.

FUEL CELL ENERGY

BACKGROUND.

The first recorded demonstration of the fuel cell principle was accomplished by Sir William Grove in 1839. Since electricity had been demonstrated to separate water into hydrogen and oxygen, he reasoned that this process could be reversed to produce electricity from hydrogen and oxygen. He experimented with this concept but had limited success. In 1889, the first real advance in this concept was made. The design was of a gaseous battery with electrodes immersed in an electrolyte solution using platinum black as the catalyst. Significant design advances were started in 1932 by Francis Bacon. He utilized metallic nickel electrodes in a potassium hydroxide solution, and operated the cell at a temperature of about 700° Fahrenheit (F) and at a pressure of 600 pounds per square inch (psi). By 1950 he was able to demonstrate a 5-kW fuel cell system.

In 1958, the first U.S. satellite utilized relatively short life storage batteries as a power source. However, for extended flights, a power source providing more power and longer life was needed; the fuel cell was selected and used in the Gemini and Apollo space programs.

Now, both industry and government organizations are focusing attention on development and demonstration of fuel cells for earth applications.

THEORY.

Similar to the dry or wet cell battery, the fuel cell functions by virtue of electrochemical reactions wherein the molecular energy of a fuel and an oxidant are transformed into direct current electrical energy. Fuel cells differ from batteries in that they do not consume chemicals that are part of or stored within their structure. Fuel cell reactants are supplied from outside the cell.

A schematic representation of a simplified fuel cell is shown in figure 12. Within the potassium hydroxide electrolyte are two porous electrodes. The electrodes provide a large number of reaction sites so that the required reactant gases, hydrogen and oxygen, can react with the electrolyte. Hydrogen (H_2) is fed into a chamber on the anode side, and oxygen (O_2) on the cathode side. When the hydrogen diffuses through the porous electrode and comes in contact with the electrolyte, which is rich with hydroxyl (OH^-) ions, it forms water. At the cathode, oxygen is reacting with the water in the electrolyte to form hydroxyl ions and electrons are removed. Due to these reactions, free electrons are left on the anode, which results in a negative charge, and electrons are removed from the cathode, which gives a positive charge.

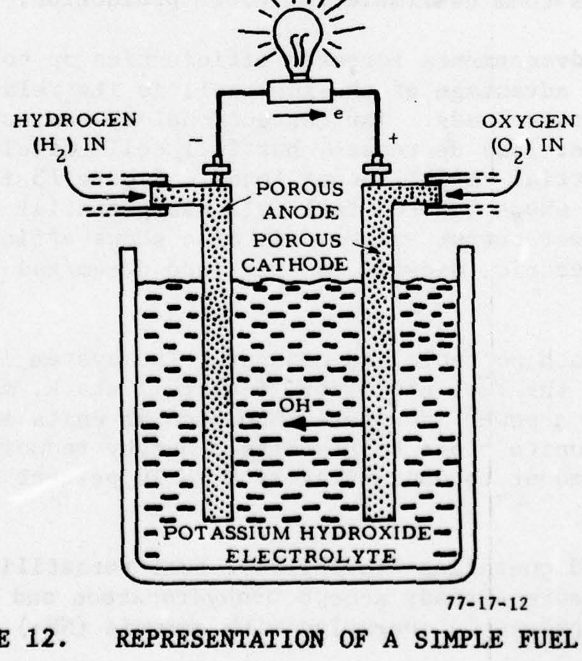


FIGURE 12. REPRESENTATION OF A SIMPLE FUEL CELL

Without an electrical connection between the anode and cathode, the reaction is allowed to achieve equilibrium (open circuit voltage), and no further reaction occurs. At this point the consumption of hydrogen and oxygen ceases. Because the electrolyte is a poor conductor, the electrons cannot travel through the electrolyte and the cell voltage is maintained. When a load is applied across the anode and cathode, the electrons are removed from the anode and the hydrogen/hydroxyl ions again combine to form water.

As the absorbed hydrogen is consumed, more hydrogen is diffused through the electrodes. At the cathode, the returning electrons facilitate the production of hydroxyl ions, which are free to move in the electrolyte. Although all of the hydroxyl ions are consumed, only half of the water formed at the anode is consumed in the cathodic reaction. The remaining water formed becomes a byproduct and must be removed. Figure 13 schematically shows the fuel cell reactions and structure.

TECHNOLOGY.

ADVANTAGES. Fuel cells have many advantages over conventional power generating systems. As shown in figure 14, unlike conventional systems, a fuel cell is a direct energy conversion from chemical energy to electrical energy. Conventional systems first convert fuel energy to thermal energy, then to mechanical energy and finally to electrical energy.

As a result of the direct energy conversion of a fuel cell, the efficiency is good. Efficiencies for contemporary systems range from 25 to 38 percent, depending upon the plant type and percent-rated load at which they operate. The conversion efficiencies of fuel cells range from 37 to 40 percent (present technology), which makes them desirable for power production.

Planned technological advancements forecast efficiencies up to the 50 to 60 percent range. Another advantage of the fuel cell is its relative efficiency when operating at low power loads. The conventional system suffers a loss in efficiency as the percent load decreases, but fuel cell efficiency remains nearly constant from partial to full power loads. Figure 15 illustrates this constant efficiency and shows how the fuel cell has potential application over a very wide range of power output values. It also shows efficiency and power relative to gasoline electric, diesel electric, and steam/gas turbine power generation equipment.

Fuel cell systems are both portable and modular. The system is comprised of three modular sections: the fuel processor, fuel cell stack, and, dependent upon load requirements, a power inverter. The modular units enable the user to quickly install the units close to his site, thereby reducing transmission line losses which can amount to approximately 8 to 10 percent of the power being transmitted.

Besides the physical and operating flexibility, fuel versatility is a major advantage. Fuel processors already accept nonhydrocarbon and hydrocarbon fuels. Fuel cells are presently operating with ammonia (NH_3), hydrazine (N_2H_4)

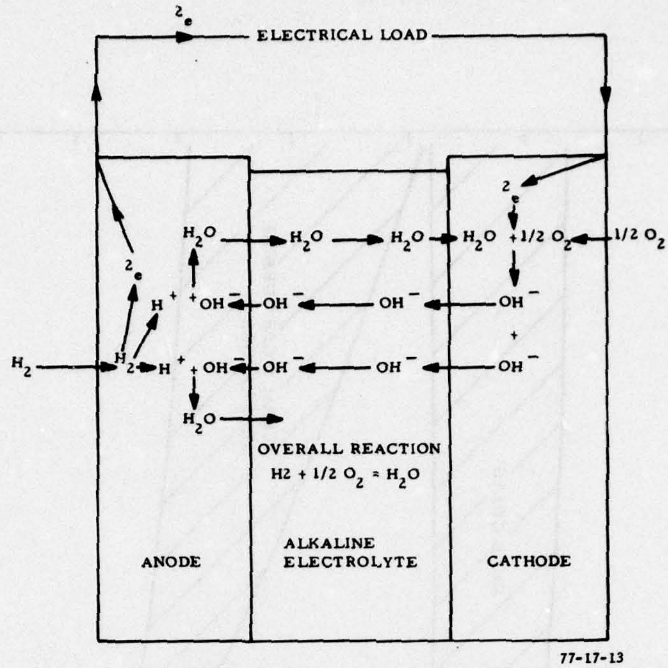


FIGURE 13. REACTIONS TAKING PLACE IN A HYDROGEN-OXYGEN FUEL CELL WITH ALKALINE ELECTROLYTE

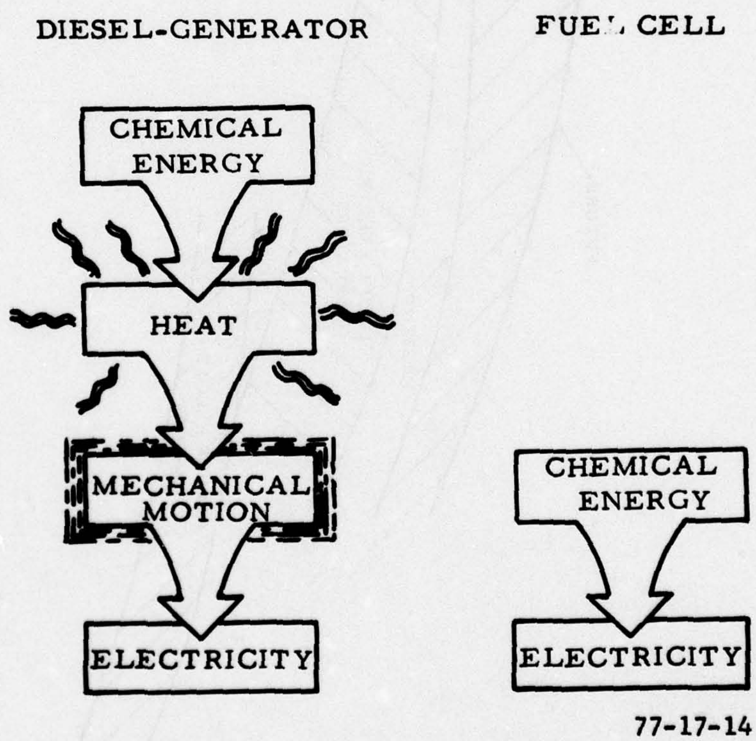


FIGURE 14. COMPARISON OF ENERGY TRANSFORMATION PROCESSES IN A DIESEL GENERATOR AND A FUEL CELL

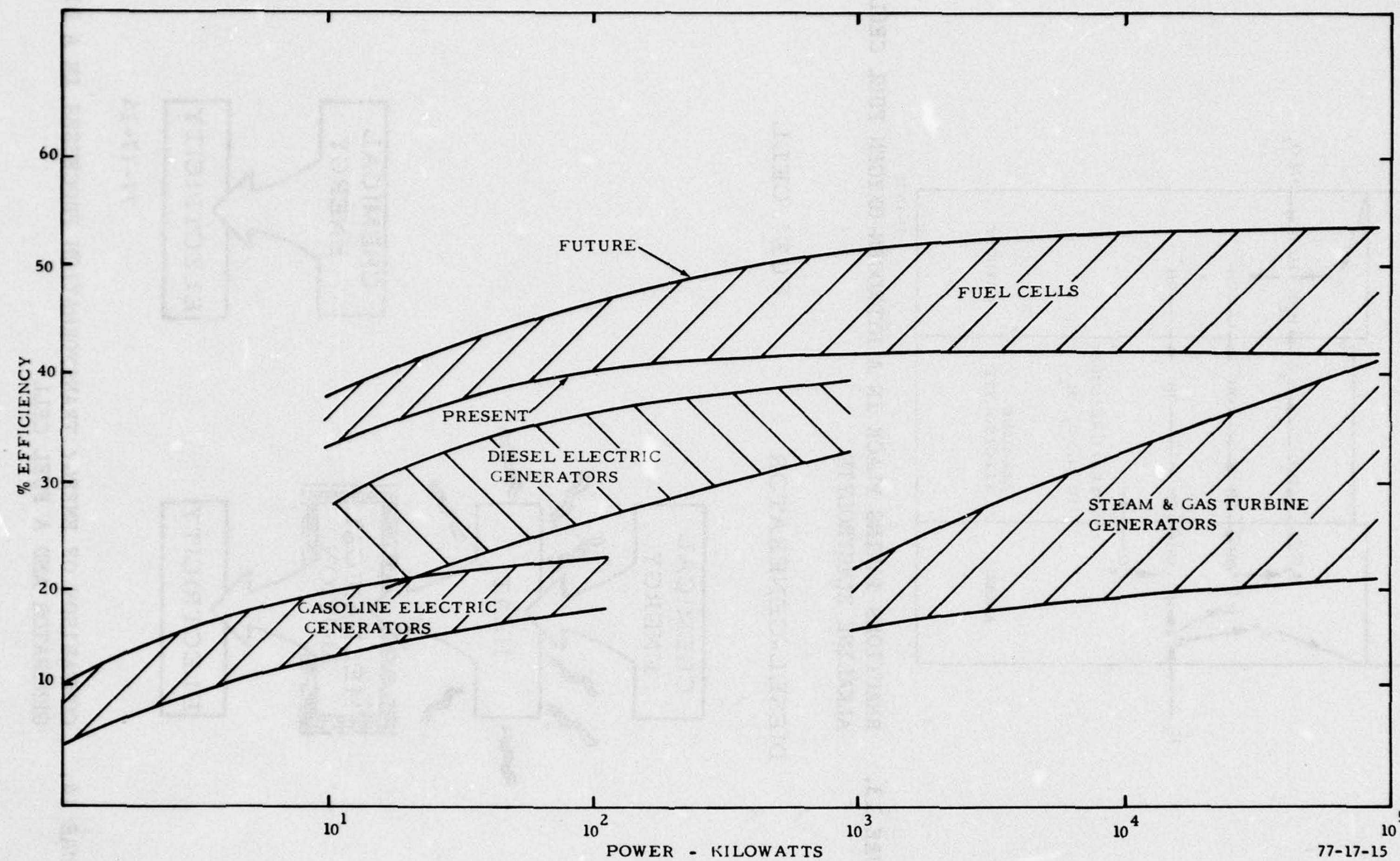


FIGURE 15. RANGES OF EFFICIENCY VERSUS POWER OUTPUT

and other nonhydrocarbon fuels and metal hydrides. Hydrocarbon fuels, like natural gas, methanol, light distillates and high, medium, or low British thermal unit (Btu) gases have been successfully processed. Work is now underway to include synthetic fuel products derived from the nations plentiful coal supply.

Another major advantage of the fuel cell is the capability of providing instant response, generating energy from the moment the demand is sensed. In addition, the d.c. produced by the fuel cell may be converted into a.c. by using a power inverter. Power inverters that can convert d.c. electricity to a.c. at nearly 96 percent efficiency are now available. Other advantages are quiet operation and low exhaust emissions. It should be noted that the emissions from the fuel cell exhaust are many times cleaner than the Environmental Protection Agency (EPA) requirements. Comparative emissions are shown in table 1.

Fossil fuel and nuclear plants generate an excessive amount of heat and require large quantities of water for cooling purposes. Fuel cells can be air cooled because they generate less heat.

The capability of fuel cells to produce electricity efficiently on both a large and small scale makes them desirable for onsite power generation. Eighty percent of the commercial and multiunit residential buildings built in the United States have a maximum power requirement under 200 kW. Onsite fuel cells could save 25 to 30 percent of the fuel required to supply conventional electricity to such buildings. Also, recovery of the by-product heat generated by the fuel cell may be used for space and water heating, which will further extend the nation's fuel resources. Figure 16 graphically illustrates that if the heat generated by the fuel cell can be utilized along with the electrical power, overall efficiency could approach 85 percent.

TABLE 1. POWER SYSTEM EXHAUST EMISSION COMPARISON

	Federal Standards			
Emission	Gas-Fired Utility Central Station	Oil-Fired Utility Central Station	Coal-Fired Utility Central Station	Experimental Fuel Cells
SO_2	No requirement	7.36	10.90	0-0.00026
NO_x	1.98	2.76	6.36	0.139-0.236
Hydrocarbons	No requirement	No requirement	No requirement	0.031-0.225
Particulates	0.98	0.92	0.91	0-0.0003

Federal standard (effective 8/17/71) values converted to pounds/1000 kW/h.

DISADVANTAGES. The most apparent disadvantage is the lack of commercial availability of fuel cells. Although significant advancements in fuel cell technology have been made, the demand for the units has not been sufficient to justify the cost of setting up production facilities.

COMMERCIAL AVAILABILITY. There are two commercially available units which are manufactured by Englehard Industries. The first is the model 15-L hydrogen/air, 12-W unit which uses phosphoric acid electrolyte. The other is the model

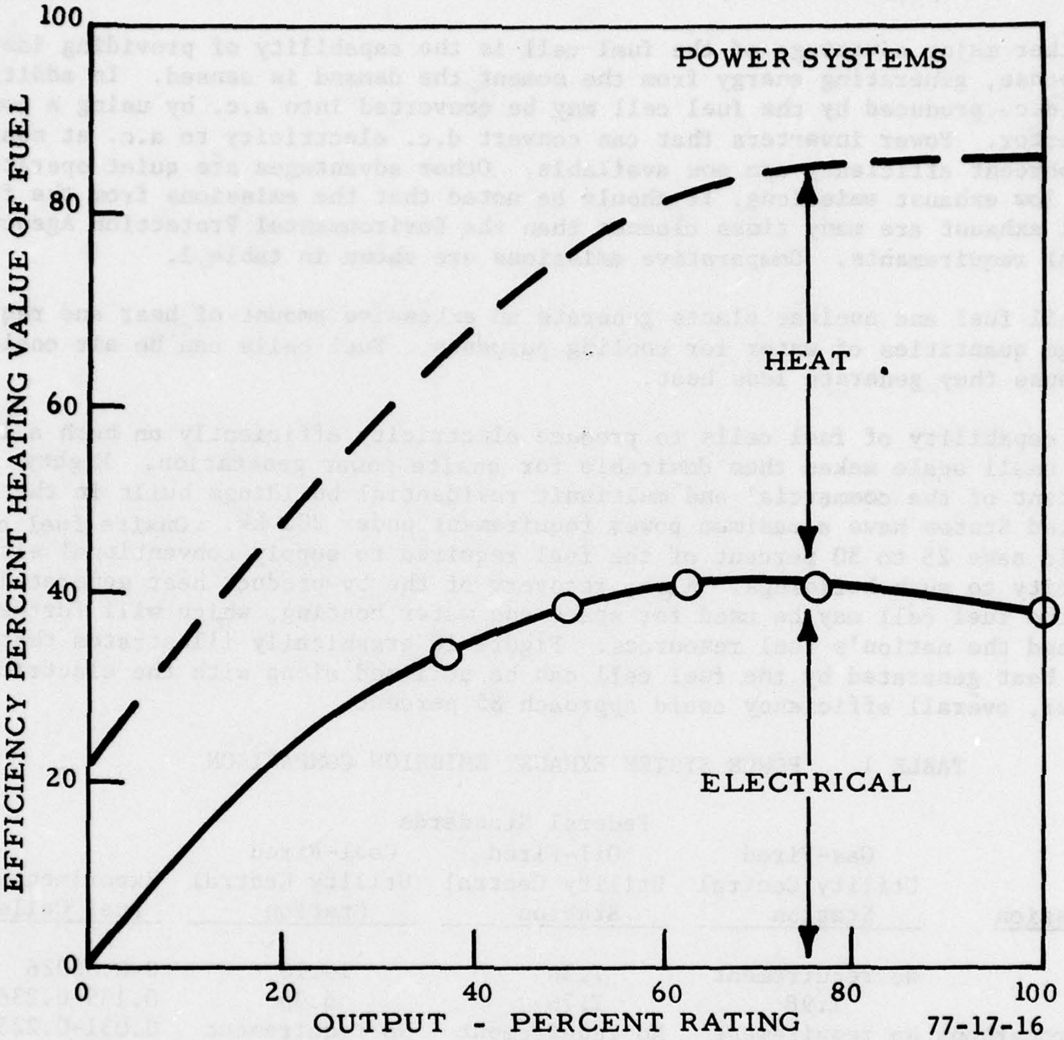


FIGURE 16. POWER PLANT PERFORMANCE WITH HEAT RECOVERY

750-A, 750-W unit also using phosphoric acid electrolyte. The cost of the model 15-L is less than $1,000, while the price of the model 750-A is in excess of $10,000.

AUXILIARY EQUIPMENT REQUIREMENTS. With the installation of a fuel cell system, certain auxiliary equipment is necessary. This could consist of a hydrogen gas generator, an inverter, valves, tubing, and relays. Fuel storage tanks are also needed, with the size and type being dependent upon the type of fuel to be used. If the fuel cell waste heat is to be utilized for heating, suitable equipment is also required to recover this heat.

INSTALLATION CONSIDERATIONS. Since the fuel cell system is small in size and weight-per-watt output, very little site preparation is required for installation. The most important installation requirement is the availability of the raw fuel for the fuel processor. Because of the large network of natural gas transmission lines and their accessibility, plus the advanced development achievements of the natural gas type fuel cells, indications are that installation does not present a problem.

MAINTENANCE. Except for air blowers that are required for cooling, relays, regulators, and valves, the fuel cell is free of moving parts. It can therefore be assumed that the fuel cell would require a minimum of maintainence. The modular concept of the fuel cell system lends itself to direct replacement and very little onsite repair.

Depending upon the type of fuel cell stack, various predictions of stack life are reported. For example, United Technologies Corporation (UTC) estimates a 20,000-hour life for its phosphoric acid electrolyte while General Electric's solid polymer electrolyte is reported to have a life in excess of 35,000 hours.

STATUS OF GOVERNMENT/INDUSTRY PROGRAMS. The United States Government, through ERDA, has a joint program with the gas companies to fund the development and procurement of fifty 40-kW natural gas type fuel cells with a heat pump, from UTC. ERDA plans to establish a development contract with Englehard Industries for the development of a 20 to 120 kW fuel cell which will use other types of fuel. MERADCOM at Fort Belvoir, Virginia has a contract with Energy Research Corporation for the procurement of twenty-two 1.5-kW methanol/air fuel cells, which will be tested as replacements for their present engine generator sets that are now in use in the field. NASA/Lewis Research Center have limited their work on fuel cells to space applications only.

The gas and electric utility companies have also funded UTC for the development of fuel cells that will range from 12.5 kW to 26 megawatts (MW). However, since these programs are proprietary to the utilities, information and data concerning these equipments are not available. Table 2 summarizes the present industry programs for fuel cells.

TABLE 2. PRESENT INDUSTRY PROGRAMS (FUEL CELLS)

Program	Funding Source	Objective	Total Program Funding (Million $)	Funding Rate (Million $/Year)
Target	United Technologies Corporation	Develop 25 to 250 kW Power Plants For On-Site Application	60	6
	Gas Utility Companies			
FCG-1	United Technologies Corporation	Develop 26 MW Power Plants For Electrical Sub-Station Application	52	12
	9 Urban/ Coastal Electrical Utility Companies			
Electric Power Research Institute Investigations	Electric Power Research Institute	Advanced (Second Generation) Technology	4 (To Date)	4 to 6
		Assessment and Fuel Processing Studies		
		Supporting R&D		

SUMMARY.

The fuel cell has several significant advantages:

a. Modularity
b. Relatively small size per kilowatt output
c. Fuel versatility
d. Good efficiency verus present conventional methods
e. Efficiency retained during load variations
f. Multipurpose use (heat as well as electrical power)
g. Potential high reliability and limited maintainability

The broad spectrum of fuel cell output capability and the specific advantages mentioned above make it a highly desirable alternative power source. When commercially available in quantities, it could be a very likely candidate for replacement of FAA diesel generators. Its use as a prime source as well as backup is also a distinct possibility.

Currently, the most extensive efforts toward development are being exerted by utility companies. In order to utilize the benefits obtainable from fuel cells for powering FAA facilities, a joint program effort with ERDA, the utility groups, and selected manufacturers must be pursued. An excellent beginning would be to negotiate with ERDA a binding agreement for obtaining one or more of the 40 kW fuel cells for use at an FAA pilot site.

THERMOELECTRIC AND THERMIONIC ENERGY

BACKGROUND.

Government research and development in thermoelectric technology is being conducted primarily by ERDA and the U.S. Naval Nuclear Power Unit at Port Hueneme, California. In addition, research in thermoelectric technology is also being conducted by Teledyne Isotopes, Timonium, Maryland; Nuclear Battery Corporation, Columbia, Maryland; General Atomic, San Diego, California; Syncal Corporation, Sunnyvale, California; Aerojet Energy Conversion Company, El Monte, California; and General Electric Company, Valley Forge, Pennsylvania. The first four companies are also performing work on Radioisotope Thermoelectric Generators (RTG). Teledyne Isotopes has also designed a thermoelectric generator using a small nuclear reactor as its heat source. This will be capable of producing power in the 200-W to 30-kW range, while operating unattended for 10 or more years. When such reactor-powered thermoelectric generators become commercially available, they should be considered as alternate power sources for FAA remote facilities where the power requirements are greater than that which can be accommodated by RTG's or Fossil-Fueled Thermoelectric Generators.

The present state of the art of thermionic conversion is not sufficiently advanced to permit economically feasible terrestrial applications. The prime terrestrial application of thermionic conversion, the topping of utility power

plants, will require conversion efficiencies of at least 20 percent at emitter temperatures of approximately 1125° C. This stage of technology is expected to be reached around 1980 and application of this technology will not be available until late 1980s or early 1990s.

Research and development in thermionic technology is being conducted primarily by two government agencies, NASA and ERDA. NASA's programs are directed toward high-powered space applications using nuclear reactor heat sources and low power space applications using radioisotopes as the heat source. ERDA's primary effort is directed toward thermionic topping of power plants. The principle commercial contractors are Thermo-Electron Corporation of Waltham, Massachusetts, and Rasor Associates of Sunnyvale, California.

Thermionic conversion studies are currently funded as a technology program at a low level. While the potential for terrestrial applications is high, this must await the attainment of lower emitter temperatures and higher efficiencies. Consequently, thermionic converters are generally not feasible for use as alternate power sources at this time.

THEORY.

Thermoelectric and thermionic energy converters are devices which convert heat directly into electricity without the use of moving parts. In the case of the thermoelectric converters, the conversion is accomplished by means of metallic or semiconductor thermocouples. The thermionic converters, on the other hand, accomplish this conversion by means of electron emission between two metallic electrodes sealed within a vapor enclosure or within a closed vacuum. The heat sources for either of these two types of energy converters can be from fossil fuels, nuclear energy (radioisotopes), or other thermal energy sources.

THERMOELECTRIC CONVERTERS. A thermoelectric converter consists of many thermoelectric couples. Each couple is composed of two elements, which may be special metal alloys or semiconductor materials.

To observe how thermoelectric couples operate, consider a single couple bonded together at one end and connected to an electrical load with a milliammeter at the other end. When heat is applied to one end of the couple and withdrawn from the other end, an electric current will be observed to flow in the milliammeter. The two elements are different in that the voltage produced is positive in one and negative in the other.

The thermoelectric couples in the converter are usually connected in series or series-parallel arrays to increase the power output. Figure 17 shows an example of series connection of couples consisting of n- and p-type semiconductor elements. By alternately bonding the n- and p-type elements as shown, the elements are seen to be connected electrically in series while remaining thermally in parallel. The current flow shown in figure 17 is that of electrical holes (positive charges). Electron flow is in the opposite direction.

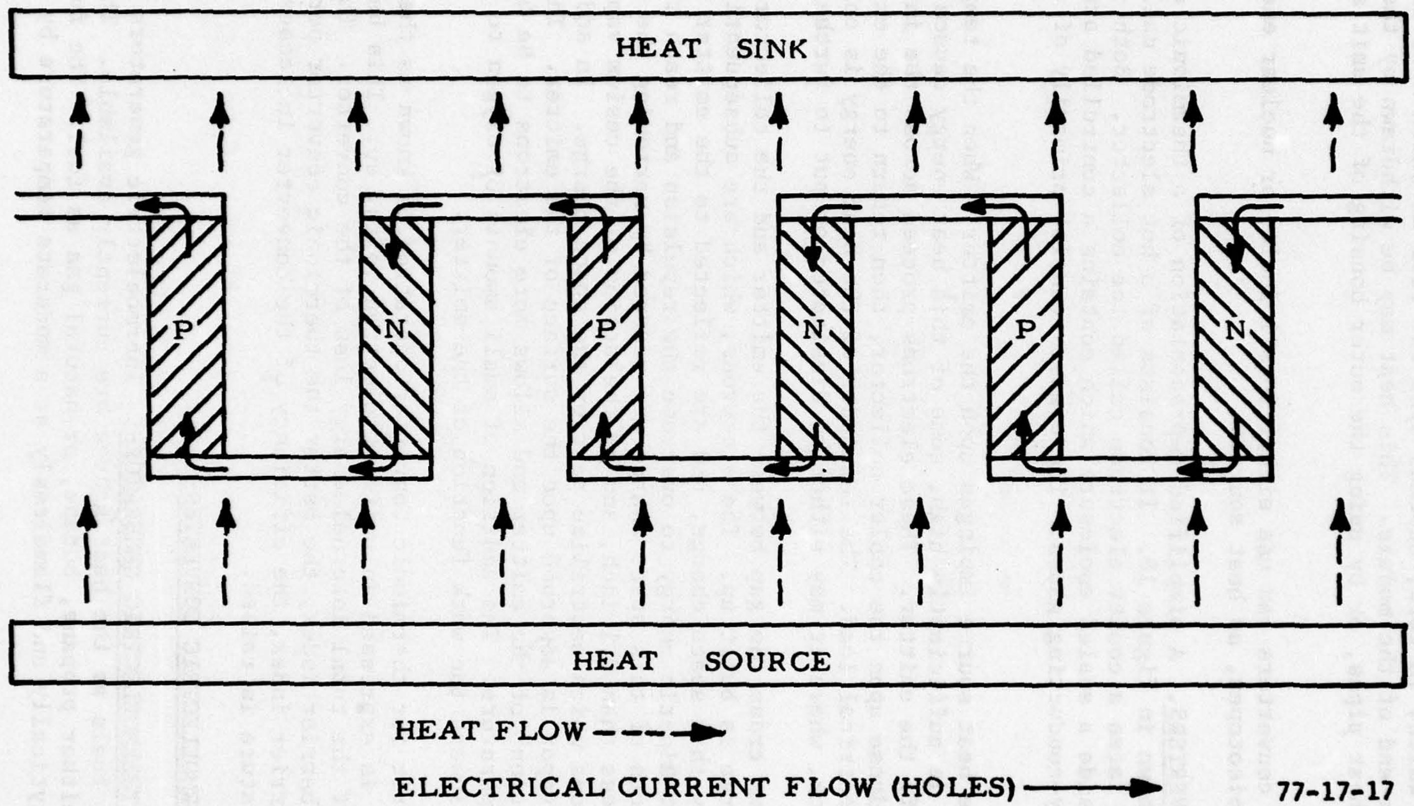


FIGURE 17. SERIES CONNECTION OF THREE THERMOELECTRIC COUPLES

In addition to the manner of connection of the thermoelectric elements, the power output will depend upon the temperature differential between the two ends of the module, which, in turn, depends upon the rate at which heat is withdrawn from the cooler end of the module. This heat may be withdrawn by the use of cooling fins, heat pipes, or by using the outer housing of the unit as a heat sink.

Thermoelectric converters can use either fossil fuels, or nuclear energy sources, including radioisotopes, as heat sources.

THERMIONIC CONVERTERS. A simplified representation of a thermionic energy converter is shown in figure 18. It consists of a hot electrode called the emitter, which faces a cooler electrode called the collector. Both electrodes are mounted inside a sealed enclosure which contains a controlled atmosphere of electrically-conducting gases. These gases consist primarily of cesium vapor.

Energy from the heat source impinges upon the emitter. When the temperature of this energy is sufficiently high, some of this heat energy causes electrons to be boiled off the emitter. These electrons proceed across the interelectrode gap, condense upon the cooler collector, then return to the emitter through the electrical load. The remainder of the heat energy is collected at the heat sink, where it may either be dissipated or put to further use.

As the electrons cross the gap between the emitter and the collector, a negative space charge is built up. The electrons, which are subsequently emitted, are repelled by this space charge, and are reflected to the emitter unless they have sufficient kinetic energy to overcome the repulsion and reach the collector. The effects of this space charge are reduced by narrowing the interelectrode gap to less than 0.1 inch, and by the action of the cesium vapor in forming positive ions which neutralize part of the space charge. In addition, some of the cesium vapor is adsorbed upon the surface of the emitter. This lowers the "work function" of the emitter and allows more electrons to be boiled off at a given temperature. The addition of small amounts of oxygen to the cesium vapor further lowers the work function of the emitter.

A figure of merit for thermionic converter operation is known as the barrier index, V_B, and is expressed in units of electron volts, ev. This barrier index is a measure of the total internal energy loss of the converter. Therefore, the lower the barrier index, the better the thermionic converter performance. For a given barrier index, the efficiency of the converter increases as the emitter temperature is raised.

TECHNOLOGY-THERMOELECTRIC CONVERTERS.

FOSSIL-FUELED THERMOELECTRIC GENERATORS. Thermoelectric generators which utilize fossil fuels as the heat source are currently available. These generators utilize either propane, butane, or natural gas as fuel. The fuel is oxidized catalytically and flamelessly at a moderate temperature by means of

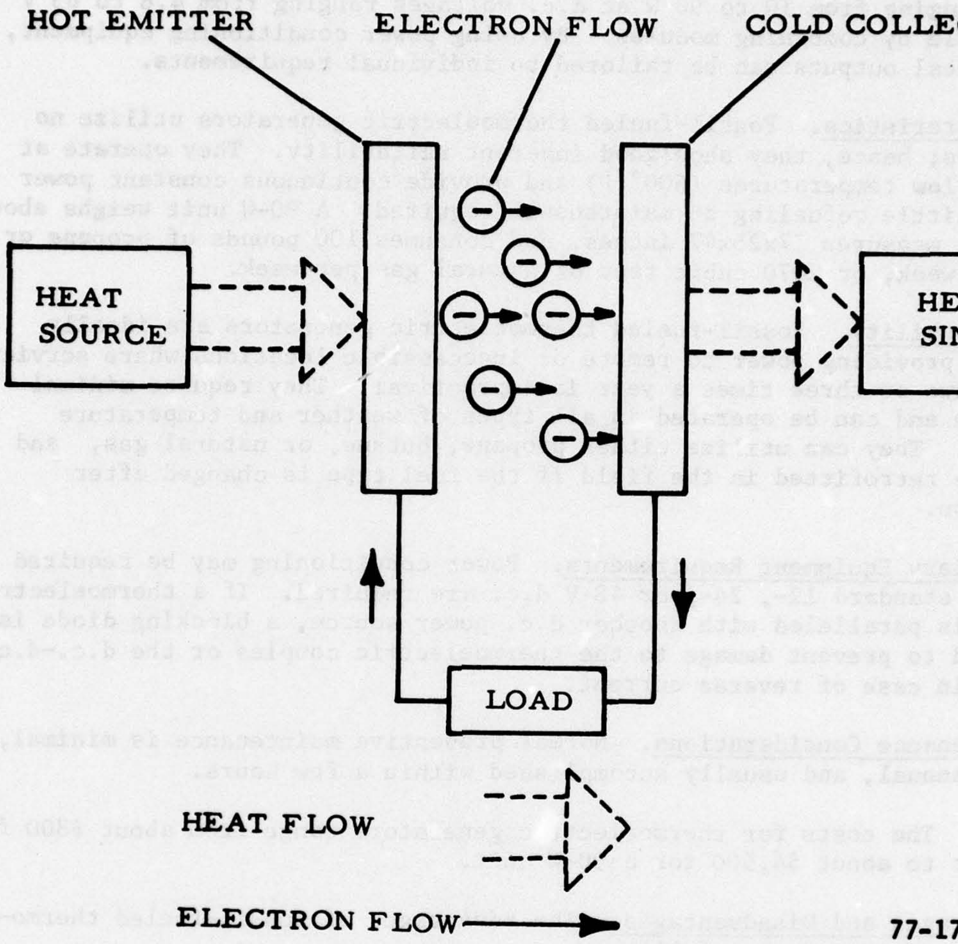


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FIGURE 18. SIMPLIFIED DIAGRAM OF A THERMIONIC ENERGY CONVERTER

platinum-coated pellets. The thermoelectric converter modules consist of bismuth telluride thermocouples. Each module produces 5 W at 2.4 V. Power capabilities ranging from 10 to 90 W at d.c. voltages ranging from 4.8 to 65 V are available by combining modules. By using power conditioning equipment, the electrical outputs can be tailored to individual requirements.

Characteristics. Fossil-fueled thermoelectric generators utilize no moving parts; hence, they show good inherent reliability. They operate at relatively low temperatures (600° F) and provide continuous constant power with very little refueling or maintenance required. A 90-W unit weighs about 180 pounds, measures 17x25x47 inches, and consumes 100 pounds of propane or butane per week, or 2070 cubic feet of natural gas per week.

Applicability. Fossil-fueled thermoelectric generators are ideally suited for providing power to remote or inaccessible locations where servicing more than two or three times a year is impractical. They require minimal maintenance and can be operated in all types of weather and temperature conditions. They can utilize either propane, butane, or natural gas, and they can be retrofitted in the field if the fuel type is changed after installation.

Auxiliary Equipment Requirements. Power conditioning may be required if other than standard 12-, 24-, or 48-V d.c. are required. If a thermoelectric generator is paralleled with another d.c. power source, a blocking diode is recommended to prevent damage to the thermoelectric couples or the d.c.-d.c. converter in case of reverse current.

Maintenance Considerations. Normal preventive maintenance is minimal, generally annual, and usually accomplished within a few hours.

Cost. The costs for thermoelectric generators range from about $800 for a 10-W unit to about $4,500 for a 90-W unit.

Advantages and Disadvantages. The advantages of fossil-fueled thermoelectric generators are as follows:

1. Inherently high reliability due to no moving parts.

2. Use of flameless combustion is advantageous in windy locations where the flame could be blown out.

3. Low operating temperatures of 600° F makes the generator safe and explosion-proof.

4. Modular construction permits power capability in 5-W increments from 10 to 90 W in a single unit.

5. They are relatively inexpensive, easy to operate and maintain, provide constant power output under all types of climatic conditions, and require minimal maintenance.

6. Fuel or air flow can be interrupted for 3 minutes or more and combustion will resume spontaneously when the system is restored.

7. Complete flameless combustion of gas leaves no dirt, soot, or other hazards associated with conventional flame combustion.

8. No radiation problems since no radioactive materials are used.

The main disadvantage of fossil-fueled thermoelectric generators is that some maintenance is necessary and periodic refueling is required.

RADIOISOTOPE THERMOELECTRIC GENERATORS. RTG's utilize radioisotopes as their heat source. In a radioisotope, heat is generated when a radioactive nucleus decays to a stable state. The amount of heat given off is a function of the quantity of the radioactive nuclei, the energy of the atomic particles omitted, and the half-life, or length of time it takes for half the unstable atoms to decay. Half-lives of various radioisotopes range from fractions of a second to thousands or millions of years. Unlike a nuclear reactor in which heat is produced by a controlled chain reaction of fissionable atomic material, the thermal power of a radioisotope cannot be regulated. The radioactive fuel in an RTG is usually compounded to provide a stable fuel form and encapsulated to prevent contamination.

Characteristics. RTG's in present use generate relatively small amounts of power ranging from a fraction of a watt to about 100 watts. But their unique feature is that this small amount of power can be produced at a continuous and nearly constant rate for periods of 15 years or more without requiring human intervention or any external source of fuel or air.

A variety of radioisotope fuels are used as the heat sources in RTG's. Plutonium-238 is used primarily for space applications because of its long life and minimum shielding requirements. Its relatively long half-life of 86 years means that there is only about a 10-percent decrease in heat output over a 10-year period, simplifying the design of generators for space use. The expense of plutonium-238 (about $500 per thermal watt) also tends to favor its use for space applications. For terrestrial application and some short term space uses, other radioisotopes of shorter half-life are used. Strontium-90, which is less expensive than plutonium 238 but which has a half-life of 28 years rather than 86 years, is widely used in terrestrial applications. Temperatures developed by these heat sources range from about 300° to 850° C.

A typical RTG used by the U.S. Navy is shown in figure 19. This RTG was designed to deliver 25 W continuously for a period of 5 years. Figure 20 shows the construction of a typical small (0.5 W) RTG used by the U.S. Navy. The outer case functions as both container and heat sink. Typical dimensions are 2 inches in diameter and 6 inches in height. Typical weights are 2 or 3 pounds.

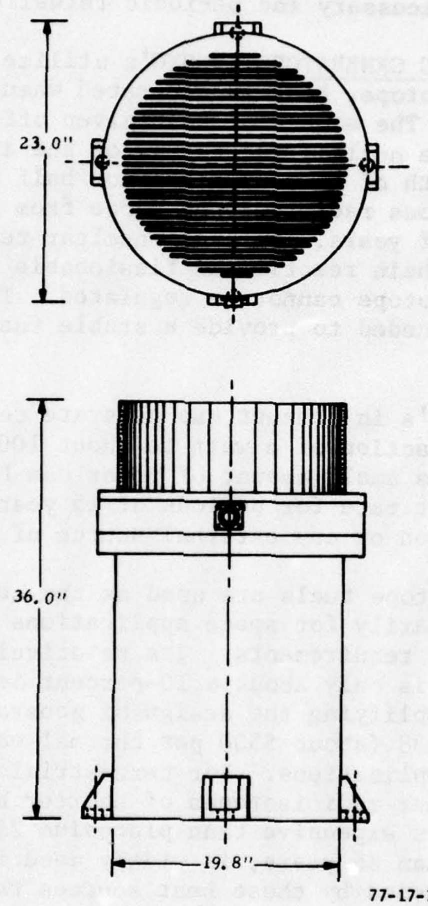

FIGURE 19. RADIOISOTOPE THERMOELECTRIC GENERATOR UTILIZED BY THE U.S. NAVY (25 W)

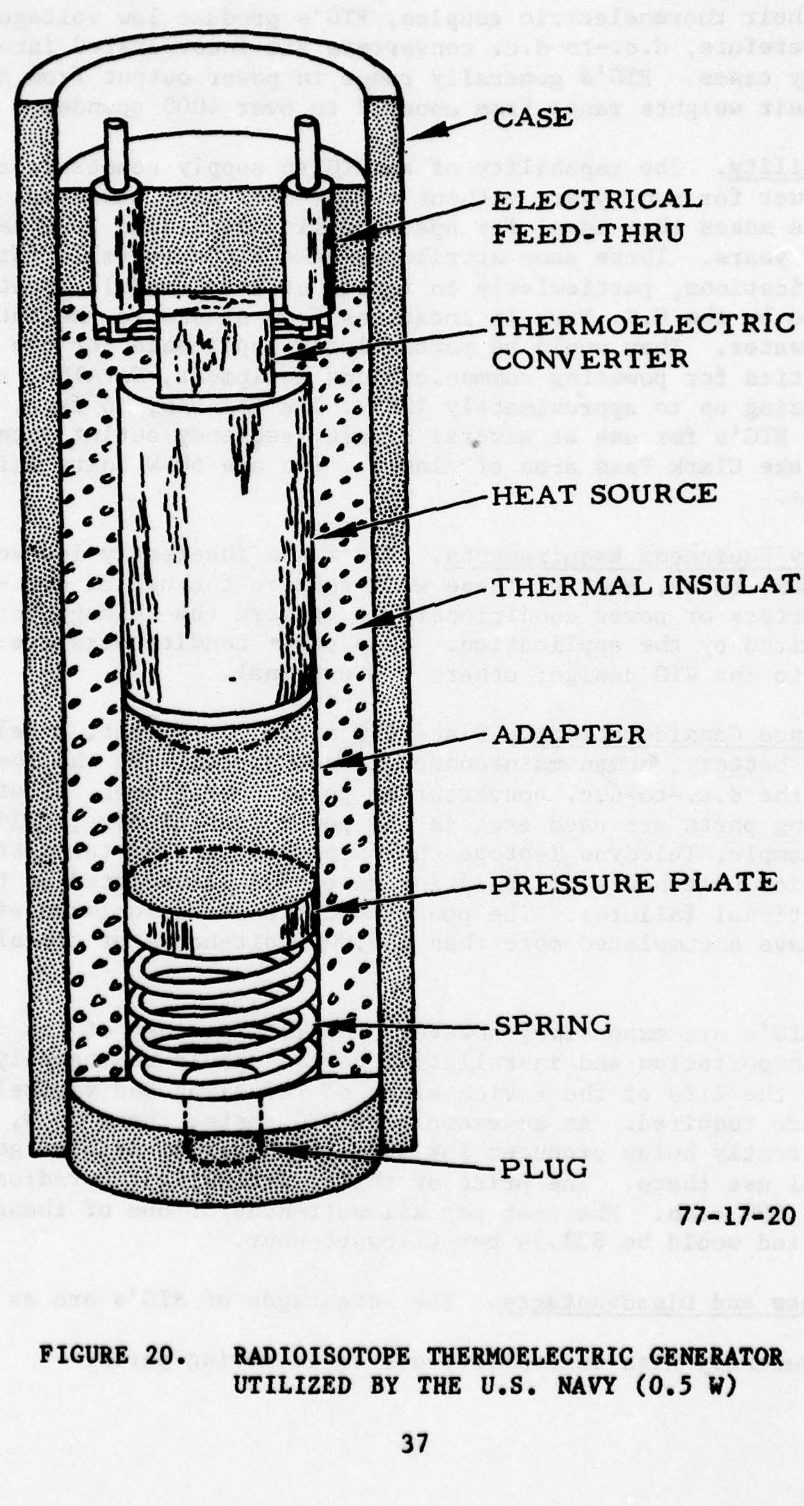

FIGURE 20. RADIOISOTOPE THERMOELECTRIC GENERATOR UTILIZED BY THE U.S. NAVY (0.5 W)

The thermoelectric converter consists of bismuth terruride, while 238 plutonium oxide is the radioisotope used in the heat source.

With the exception of RTG's utilizing silicon-germanium alloys as the elements in their thermoelectric couples, RTG's produce low voltages and high currents. Therefore, d.c.-to-d.c. converters are incorporated into the RTG design in many cases. RTG's generally range in power output from about 0.5 to 100 W. Their weights range from about 2 to over 4000 pounds.

Applicability. The capability of an RTG to supply constant, continuous, electrical power for many years without the need of air, sunshine, refueling, or maintenance makes them ideal for space applications, and they have been so used for many years. These same attributes make RTG's suitable for many terrestrial applications, particularly in remote or inaccessible locations. They are being used by the U.S. Navy in locations from Alaska to the Antarctic as well as underwater. They would be particularly applicable for use at FAA remote facilities for powering communications equipment, NAVAIDS, and similar devices utilizing up to approximately 100 W. The FAA has, in fact, recently obtained five RTG's for use at several single frequency outlet sites in the mountainous Lake Clark Pass area of Alaska. Two are 60 W units while three are 25 W units.

Auxiliary Equipment Requirements. RTG's are inherently low-voltage, high-current devices; hence, most of these will require the use of d.c.-to-d.c. voltage converters or power conditioners to convert the voltage to the level and type required by the application. Some power conditioners are internal and integral to the RTG design; others are external.

Maintenance Considerations. Since RTG's are, in effect, a self-contained, long-duration battery, human maintenance is not needed with the possible exception of the d.c.-to-d.c. converter or power conditioner, if utilized. Since no moving parts are used even in the power conditioners, reliability is high. For example, Teledyne Isotopes has produced over 30 terrestrial RTG's. Over two million unit-hours of operation have been accumulated on these RTG's with no operational failures. The power conditioners associated with some of these RTG's have accumulated more than 560,000 unit-hours of trouble-free operation.

Cost. RTG's are expensive; however, the initial cost of the device, including transportation and installation costs, should be the only expense involved over the life of the device since no refueling and virtually no maintenance are required. As an example of RTG costs, three 25 W, 1400-pound RTG's are currently being produced for sale to the Saudi Arabian government for meteorological use there. The price of these, including the radioactive fuel, is about $135,000 each. The cost per kilowatt-hour of one of these RTG's over a 10-year period would be $33.34 per kilowatt-hour.

Advantages and Disadvantages. The advantages of RTG's are as follows:

1. Inherently high reliability due to no moving parts.

2. Fuel and converter modules are contained in one package which can withstand severe environmental and temperature conditions.

3. Can supply nearly constant continuous power for extremely long periods of time.

4. Requires no refueling, maintenance, or other human intervention.

The disadvantages are as follows:

1. Initial cost is very high; however, this can be amortized over a long period of time.

2. Generally applicable only to low-power applications (less than 100 W).

3. Generally produces low voltages. Use of d.c.-to-d.c. converters to raise the voltage results in lower conversion efficiency as well as increased size and weight and reduced reliability.

4. Continuous heat removal required to prevent damage to thermoelectric elements.

5. Possible radiation problems

TECHNOLOGY-THERMIONIC CONVERTERS.

CHARACTERISTICS. A typical output of a thermionic converter with a 0.1-inch interelectrode gap is 5 W per square centimeter of emitter area. Hence, a thermionic converter with an emitter area of 20 square centimeters would deliver 100 W of electric power (100 amperes at one volt). Since thermionic converters produce power at high currents and low voltage, to obtain higher voltages, the converters must be series-connected.

Most nuclear-heated thermionic converters have much smaller interelectrode gaps (0.002 inches), thereby providing much higher power densities (15 to 20 W per square centimeter).

APPLICABILITY. Up to this time, thermionic converters have been used primarily in conjunction with nuclear reactor heat sources for spacecraft power systems. Adaptation of thermionic converters for terrestrial uses will become feasible as the barrier index, V_B, is lowered as a result of research and development. Various improvements in technology have resulted in a steady decrease of the barrier index with time. In 1960, for example, the barrier index was about 2.9 e_V. This yielded an efficiency of only 5 percent at 1800° C. By 1970, the barrier index had been reduced to about 2.1 e_V, corresponding to an efficiency of 20 percent at 1800° C. As the barrier index is further reduced, the resulting lower heat requirements and higher efficiencies should make thermionic converters economically and technologically feasible for many terrestrial applications. The most promising of these appear to be thermionic topping of steam power plants. Thermionic converters are suitable for this

purpose because they can utilize the heat of the fossil fuels which is currently wasted and generate more electricity from it. Combustion of the oil or coal in the steam generator of the power plant occurs at temperatures of about 1650° C. The inlet temperatures of conventional steam cycles are about 540° C. The available energy contained between these two temperature ranges is currently not being effectively used. Thermionic topping would convert some of this extra heat energy into electricity before the steam is applied to the turbines, thereby increasing the overall efficiency of the steam power plant from about 40 to 50 percent or higher. The estimated cost of this incremental power is estimated at $160 per kilowatt.

ADVANTAGES AND DISADVANTAGES. While thermionic converters are not as yet practical for consideration as alternate power sources, inherently they possess the following advantages:

1. High reliability due to no moving parts.

2. Modularity which allows thermionics to be applied over a wide power range.

3. Can be used with fossil fuels, nuclear energy, including radioisotopes, or other thermal energy sources.

4. Has potential for high efficiencies at reasonable cost.

5. Has history of steady improvement in performance.

6. Does not require storage of generated power as long as heat source remains constant.

7. Conversion media are not consumed in the energy conversion process.

The disadvantages are as follows:

1. Technology not sufficiently advanced so as to be practical at this time.

2. Relatively high emitter temperatures (1300° C or higher) which contributes to metal fatigue.

COMMERCIAL AVAILABILITY. Not commercially available as an off-the-shelf item at the present time.

AUXILIARY EQUIPMENT REQUIREMENTS. Thermionic converters produce low-voltage, high-current d.c.; hence, d.c.-to-d.c. converters or d.c.-to-a.c. inverters may be required to obtain necessary voltages. If used with a constantly available heat source such as fossil fuel, nuclear reactors, or radioisotopes, electric power would be constantly available and would obviate the need for storage media, such as batteries.

MAINTENANCE CONSIDERATIONS. Since no moving parts are involved, maintenance should be minimal. Ten to 12,000-hour lifetimes have been achieved with thermionic converters while lifetime projections of 20,000 hours are forecasted by next year.

SUMMARY.

1. Both thermoelectric and thermionic generators can utilize fossil fuels or nuclear sources including radioisotopes for heat sources.

2. Thermoelectric generators utilize bielement metallic alloy or semiconductor couples, while thermionic generators operate by electron emission from a hot emitter.

3. Thermoelectric and the thermionic generators are alike in that neither uses moving parts for the heat-to-electricity conversion; hence, the inherent reliability of both types of devices is high.

4. The most common uses of thermoelectric generators today is in conjunction with radioisotopes and gaseous fossil fuels.

5. Fossil-fueled thermoelectric generators capable of supplying up to 90 W per unit are less expensive than RTG's but require some minimal refueling and maintenance.

6. RTG's can supply power up to about 100 W at nearly constant rates for 10 to 15 years without the need of maintenance or refueling.

7. RTG's are currently in use in remote and inaccessible places from Alaska to the Antarctic.

8. RTG's are very expensive; however, since costs are one time only, they can be amortized over a 10- or 15-year period.

9. Nuclear-reactor-powered thermoelectric generators capable of providing 200 W to 30 kW for 10 years or more of unattended operation are currently in the design stage.

10. Thermionic efficiency varies directly with temperature and inversely with the barrier index. Research and development is currently directed toward reducing the barrier index. This will produce higher efficiencies at lower emitter temperatures.

11. Thermionic conversion is used chiefly for space applications today. Major terrestrial use will be thermionic topping of steam power plants when the barrier index is sufficiently reduced. The technology for this should be ready by early 1980s, with practical application not until late 1980s or early 1990s.

STORAGE BATTERIES

BACKGROUND.

Photovoltaic cells produce electricity during daylight hours only. Likewise, wind-driven generators supply electric power only when winds of sufficient velocity are available. To be able to supply this electrical energy to an electrical load at all times, some means of regulating this energy is necessary. Storage batteries are a means of doing this, since they can store some of the energy generated by the photovoltaic cells or wind-driven generators while they are operating. When the photovoltaic cells or wind-driven generators are not operating, the electrical load is then supplied by the stored energy from the batteries.

Storage batteries, along with fuel cells and thermoelectric generators, are sources of constantly-available electric power. However, the electrical loads that they supply often require different types of electric power than those produced by these sources. The sources produce steady d.c. power at relatively low voltages. Many of the loads require standard 115 V, 60 Hz a.c. power. To meet this need, inverters are interposed between the sources and the loads. The inverter changes the low d.c. voltage produced by the source to the higher a.c. voltage required by the load.

When the load requires a substantially higher d.c. voltage than that which could be practically obtained by series-connecting several sources, a d.c.-to-d.c. converter is then interposed between the source and the load. The d.c.-to-d.c. converter mechanically or electronically changes the low d.c. voltage of the source into the higher d.c. voltage used by the load. They may also be used where similar or lower d.c. output voltages are desired, and offer the advantages of isolation and very tight voltage regulation.

Many electrical loads require that their input voltages remain within certain specified tolerances, regardless of either fluctuations in magnitude of the voltages produced by the sources, or changes in value of the load impedances. To accomplish this, voltage regulators are interposed at one or more stages between the output of the source (battery, fuel cell, etc.) and the input to the electrical load.

Further discussion of storage batteries is presented while discussion of auxiliary equipment associated with electrical power sources, i.e., inverters, d.c.-to-d.c. converters, and voltage regulators is contained in appendix A.

THEORY.

An electric battery consists of two or more electric cells. A cell basically consists of two dissimilar materials (reactants) in contact with an electrically-conducting (ionic) solution called an electrolyte. When these reactants are connected by an external circuit, a chemical reaction occurs in which there is a transfer of electrons from one reactant to the other. The reactant which loses electrons is oxidized; the one which accepts electrons is reduced. All electric cells operate on this mutual reduction-oxidation (redox) principle. The electrons from the oxidized reactant flow to the reduced reactant through the external circuit or electrical load; this constitutes the useful current output of the cell. The electric current flow is internally completed inside the cell by the movement of electrically-charged chemical compounds (ions) through the electrolyte from the reduced reactant to the oxidized reactant.

This may be illustrated by the simple zinc-mercuric oxide cell shown in figure 21. The reactants are metallic zinc (Zn) and mercuric oxide (HgO). These are immersed in an electrolyte consisting of a potassium hydroxide (KOH) solution. The potassium hydroxide solution actually consists of potassium (K^+) and hydroxide (OH^-) ions.

The zinc reactant comprises the negative electrode, or anode, of the cell. The electrochemical reaction taking place at the anode consists of the oxidation of the metallic zinc by two hydroxide ions to form zinc oxide and water, liberating two electrons which flow through the external circuit. This reaction may be represented chemically by the following equation:

$$Zn + 2OH^- \longrightarrow ZnO + H_2O + 2e^-$$

The mercuric oxide is physically mounted on the positive electrode or cathode. Here, the two electrons which have travelled through the external circuit are removed by the mercuric oxide in the presence of water, reducing the mercuric oxide to mercury and producing two hydroxide ions. These replace the two hydroxide ions which were used up at the anode in oxidizing the zinc. The cathode reaction may be expressed chemically as follows:

$$HgO + H_2O + 2e^- \longrightarrow Hg + 2OH^-$$

Thus, the electrochemical reaction in this simple Zn/HgO cell may be summarized as follows:

1. Electrons flow continuously in the external circuit from anode (-) to cathode (+). This comprises the useful electrical current output of the cell.

2. Water is generated at the anode and consumed at the cathode.

3. The hydroxide ion is generated at the cathode, transferred through the electrolyte, and consumed at the anode.

In addition to an alkaline substance such as potassium hydroxide, electrolytes may consist of acid solutions such as sulfuric acid in water. Electrolytes may also consist of nonaqueous organic solvents containing inorganic ionic solutes, or may consist of fused salts, solutions of salts in ammonia, or even gases.

The theoretical open-circuit voltages of a cell are determined solely by the nature of the anode and cathode reactions and are independent of the size of the cell. Generally, these open-circuit voltages vary between one and two volts. Higher voltages may be obtained by connecting cells in series and more current may be obtained either by increasing the size of the cells or connecting them in *parallel*.

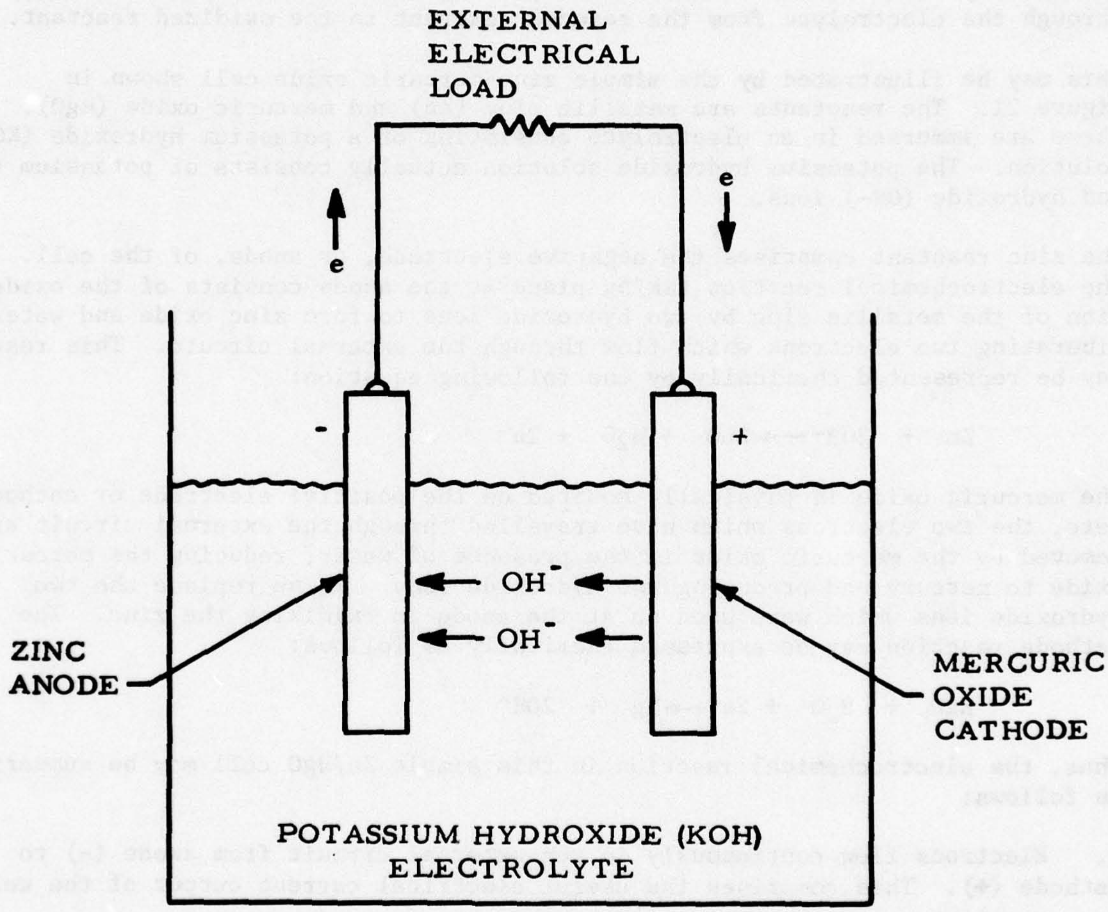

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FIGURE 21. SIMPLIFIED ELECTRIC CELL OPERATION

SECONDARY CELLS. The cell illustrated in figure 21 is a primary cell. It will continue to generate electricity (electrons) until one or both of the reactants are used up. Then the cell is exhausted and is usually discarded.

In secondary cells, the electrochemical reactions are reversible. After the electrical energy has been expended from the battery (discharge), the process may be reversed by pumping electric current through the cell in the opposite direction. This is referred to as charging the cell. Thus, the anode which was oxidized during the discharge of the cell is now reduced during the charging process, and vice-versa. It is this capability of being able to restore the chemical energy content of a secondary cell by electrical charging which makes the secondary cell so well suited for storing excess electrical energy for later use when required. Consequently, only secondary cells or storage batteries, as they are generally called, will be considered in this discussion of electrical storage.

TECHNOLOGY.

BATTERY TYPES. There are many different types of secondary batteries. The two types in most common use today are the lead-acid and nickel-cadmium batteries. Many newer types of batteries, such as nickel-hydrogen, silver-zinc, sodium-sulphur, and others have much greater energy densities and other advantages over the older lead-acid and nickel-cadmium batteries, but economically and technologically, they are not as yet competitive with the older types. A description of some of these battery types follows.

Lead-Acid Battery. The lead-acid battery is the oldest and most widely used storage battery type; hence, its technology is well developed. The lead-acid cell, when charged, consists of a spongy lead anode and a cathode made of lead peroxide. The electrolyte is a solution of sulfuric acid in water. When fully charged, the specific gravity of the electrolyte varies between 1.25 and 1.27. Cell voltage is slightly higher than two volts.

During discharge, the spongy lead anode is oxidized to lead sulphate, while the lead peroxide cathode is reduced to lead sulphate. Sulphuric acid is used up in the discharge process, reducing the concentration of the acid in the electrolyte. When completely discharged, the specific gravity of the electrolyte is reduced to between 1.13 and 1.15.

Lead-acid batteries are available in different types. In the wet-cell form, the level of the electrolyte must be periodically maintained above the level of the electrodes. This is done by adding distilled water through capped openings in the top of the cell. Modern lead-acid cells are now available in sealed and gelled electrolyte forms.

Nickel-Cadmium Battery. Nickel-cadmium batteries consist of a metallic cadmium anode, a cathode made of nickelic hydroxide, and a potassium hydroxide electrolyte. The electrodes are made by compressing a fine nickel powder onto a wire screen (sintering). These are then impregnated with the appropriate anodic and cathodic materials.

During charge and discharge cycles, the electrodes change chemically but not physically, as is the case with lead-acid batteries. Therefore, the electrodes of the nickel-cadmium battery have long life. The capacity of nickel-cadmium cells is determined by the amount of active material (nickelic hydroxide) on the cathode. The voltage of a nickel-cadmium cell is about 1.2 volts and remains fairly constant about that value during discharge. The state of charge of nickel-cadmium batteries is frequently determined by use of a third electrode.

High-Energy-Density-Battery. Battery technology has been challenged by the need of lighter improved batteries for use in electrical vehicle propulsion and also in electric utility load leveling. The electric load leveling application is similar to FAA's use of batteries as energy storage media but on a much larger scale. Excess electrical energy produced by the utility's generators during periods of light load would be stored in large batteries, which would later apply the energy to the load during peak demand periods.

As a result of this challenge, many exotic high-energy-density batteries are being developed. In general, these batteries consist of an active high-potential anode material which gives up many electrons, a low-density cathode material which accepts large numbers of electrons per unit weight, and an electrolyte system compatible with both. The anodes consist of light metals with a high electrode potential and a low equivalent weight. The most commonly used anode materials are lithium, sodium, aluminum, and calcium. Cathode materials include metal halides, metal oxides, air or oxygen, and various organic materials. Electrolytes for such high energy density batteries consist of inorganic salts. Alkali metals used as anodes preclude the use of aqueous electroytes; therefore, molten salts, sodium-ion-conducting solid electrolytes, or organic solvents containing ion salts are used instead. These electrolytes require higher operating temperatures (300 to 400° C), although the molten electrolytes have a higher ionic conductivity which is required for the high energy density batteries.

While these battery types are not at this time technologically or economically competitive with the more established lead-acid and nickel-cadmium types, they have potential for future application. A few examples of these battery types will be described as follows:

1. Lithium-Sulphide Battery - This battery is being developed for electric utility load leveling applications by the Atomics International Division of Rockwell International. It uses a lithium-silicon solid alloy as the anode, a mixture of iron sulphides as the cathode, and a molten-salt electrolyte. A lithium-sulphide battery would have one-sixth the weight and one-fourth the volume of a lead-acid battery of equal capacity. The long range objective is a 5 to 10 megawatt-hour battery for utility load-leveling use by 1980.

2. Nickel-Hydrogen Battery - This battery uses the nickelic hydroxide cathode of the nickel-cadmium battery, but uses hydrogen gas as the anode. The battery is hermetically sealed, as hydrogen is being generated during charge

and consumed at discharge. The state of charge of this battery can thereby be determined instantaneously by means of a hydrogen pressure sensor.

This battery has greater energy and power densities than the nickel-cadmium battery. It has long cycle life and deep depth of discharge capability. Its relatively high cost has restricted its use to military and aerospace applications.

3. Sodium-Sulphur Battery - This battery has 10 to 15 times the energy density of a lead-acid battery. It is being especially considered for electric vehicle propulsion. Both reactants operate in a molten state at a relatively moderate temperature of 300° C. A special ceramic electrolyte which conducts sodium ions is used to separate the molten reactants. This reversal in the usual physical states of reactants and electrolyte eliminates the shredding and physical deterioration that occurs with solid reactants.

Other batteries which are considered as candidates for solar and wind power storage applications are silver-zinc and silver-cadmium batteries. The silver-cadmium battery has twice the energy density of the nickel-cadmium battery, but suffers from low cell voltage and poor voltage regulation. The silver-cadmium cell is a compromise between the short-life, high-energy-density, silver-zinc cell and the long-life, lower energy density, nickel-cadmium cell.

<u>CHARACTERISTICS</u>. Secondary or storage batteries have certain characteristics by which they are often described or classified. Some of the major characteristics are described in the following paragraphs.

<u>Capacity</u>. The capacity of a battery is the amount of electricity it contains when fully charged. The capacity is expressed in ampere-hours (Ah), and will often be stated for a specified rate of discharge. For example, a battery may have a rated capacity of 100 Ah when discharged at a 5-hour rate, that is, when used with a load which would discharge the battery after 5 hours of continuous use. If the battery was used with a load which drew more current, causing it to become discharged after only 1 hour of continuous use, it would probably have a lower capacity for this 1-hour discharge rate, perhaps only 80 or 85 Ah.

<u>Charge Rate</u>. The charge rate of a battery is the charging current expressed as a function of the capacity of the cell or battery. For example, the 20 hour charge rate of a 10-Ah battery would be equal to 10/20=0.5 ampere charging current.

<u>Discharge Rate</u>. The current at which a cell or battery is discharged is frequently expressed as a function of its rated capacity. For example, the 0.5 hour discharge rate of a 5-Ah cell would equal a discharge current of 5/0.5=10 amperes.

<u>Cycle Life</u>. A cycle is defined as a sequence of battery charging followed by battery discharge. The cycle life of the battery is the number of these cycles, or charge and discharge sequences the battery can undergo before failure occurs. Failure of the battery can be either complete, as when one

of the cells has an internal short, or it can be defined as a reduction of Ah capacity of the battery below a certain acceptable level.

Depth of Discharge. This is defined as the percentage of rated capacity to which a cell or battery is discharged. For example, if 5 Ah of capacity is discharged from 100-Ah battery, the depth of discharge is 5 percent.

Energy Density. A figure of merit in common use with batteries is the total energy expressed as a function of the weight and volume (watt-hours/pound and watt-hours/inch^3).

Charging. In charging a battery, the charging source must deliver a d.c. voltage greater than the open-circuit voltage of the battery. Two general methods of battery charging are the constant-current and constant-voltage methods.

Constant-Current Charge. Constant-current charging is the result of a relatively constant voltage divided by a relatively constant resistance. The relatively constant values are achieved by using charging source voltages and resistances which are large with respect to the corresponding battery values. The principle of constant current charge can be illustrated with the simplified representation shown in figure 22. As seen in this figure, the battery voltage varies around 2 volts. These variations, $\pm$ V, are quite small compared to the 12 volt open circuit voltage of the charging source. Therefore, the total voltage impressed across the source and battery resistance $R_s + R_b$ will be 12 - (2 $\pm$ V) volts, or a relatively constant value of 10 volts. By similar analysis, the total resistance in the circuit will be slightly greater than 5 ohms (5 + 0.1 $\pm$ R). The charging current will, therefore, be a constant value slightly less than 10/5, or 2 amperes.

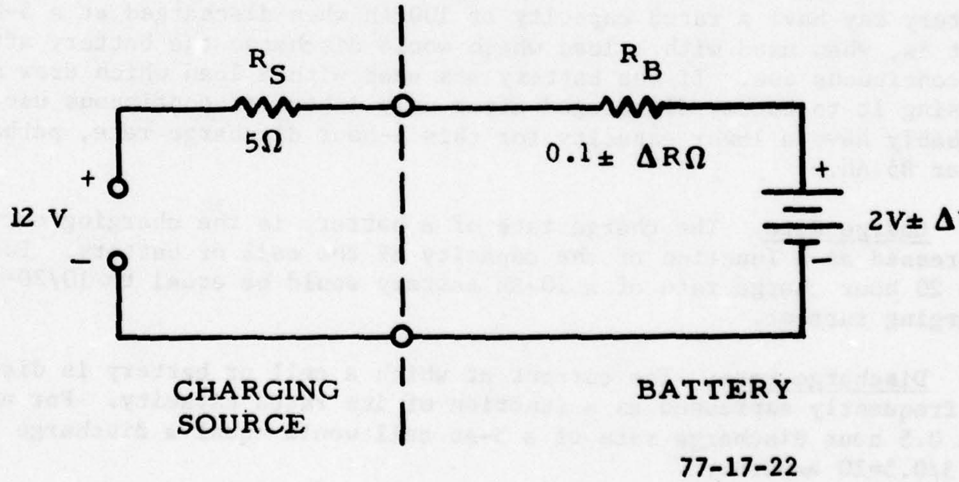

FIGURE 22. SIMPLIFIED PRINCIPLE OF CONSTANT-CURRENT BATTERY CHARGING

Constant-Voltage Charge. Constant-voltage charging involves clamping the charging voltage at a constant level. This is illustrated in figure 23, to 6.8 volts. As the battery charged, its voltage rises, thereby causing the charging current to fall exponentially.

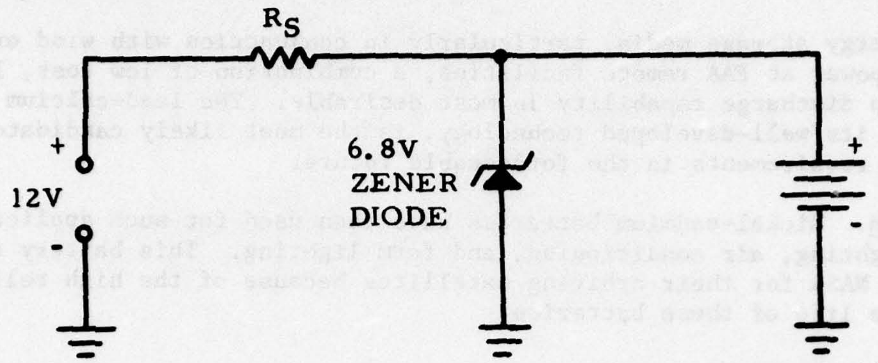

FIGURE 23. SIMPLIFIED PRINCIPLE OF CONSTANT-VOLTAGE (FLOAT) BATTERY CHARGING

A constant-current charge is generally applied first until the battery is nearly charged. Charging is then completed by means of the constant-voltage charge. Constant-voltage charging is usually used with automobile batteries, the battery being kept in a charged state from the generator when the engine is operating. This is known as "float" charging.

Charge State Detection. The state of charge of a battery can be detected by various means. One of the most common methods, used particularly in automobile batteries, is by the use of a hydrometer, which measures the specific gravity of the electrolyte. Another method of charge state detection is sensing for the presence of gases by use of a third electrode, which has a potential that varies relative to one of the regular electrodes of the battery (anode or cathode). This potential varies with gas pressure. Battery charging is automatically terminated when the potential of the third electrode reaches some predetermined level. Use of ampere-hour meters during both charge and discharge is still another method of determining the state of charge of a battery. By knowing the measured amount of ampere-hours applied to the battery during charge and removed during discharge, the instantaneous state of charge of the battery can be determined.

APPLICATIONS.

LEAD-ACID. Lead-acid batteries have been used in automobiles for many years. As stated previously, automobile batteries are designed to be "float" charged; hence, they were not designed either for deep depth of discharge or for long cycle life. However, they are relatively inexpensive, costing approximately $20 per kilowatt-hour.

Larger, more ruggedly constructed lead-acid batteries have been built for marine and industrial use. They can be operated to a greater depth of discharge and have a longer life (20 years or 4000 to 5000 charge/discharge cycles), but are more expensive.

For use as energy storage media, particularly in conjunction with wind or photovoltaic power at FAA remote facilities, a combination of low cost, long life, and deep discharge capability is most desirable. The lead-calcium battery, with its well-developed technology, is the most likely candidate for meeting these requirements in the foreseeable future.

NICKEL CADMIUM. Nickel-cadmium batteries have been used for such applications as vehicle lighting, air conditioning, and farm lighting. This battery type was chosen by NASA for their orbiting satellites because of the high reliability and long cycle life of these batteries.

ADVANTAGES.

LEAD-ACID BATTERY.

1. Technology is well advanced and constituent materials are cheap and plentiful.

2. Sealed and gelled electrolyte batteries require minimal maintenance and can be operated in any physical orientation.

3. Least expensive of battery types.

NICKEL-CADMIUM BATTERY.

1. Long shelf life.

2. Constant voltage over normal discharge time.

3. Can be discharged to a greater depth and shows longer cycle life than lead-acid batteries.

4. Higher rate discharge capability than lead-acid batteries.

5. Electrodes do not disintegrate with cycling as is the case with lead-acid batteries.

DISADVANTAGES.

LEAD-ACID BATTERY.

1. Wet cells require periodic checking of electrolyte level.

2. Corrosion of cathode due to flaking off of the lead peroxide formed

3. Sulphation, due to flaking off of the lead sulphate on discharge.

4. Overcharging can produce explosive hydrogen gas.

NICKEL-CADMIUM BATTERY.

1. More expensive than lead-acid batteries because of constituent material costs.

ADDITIONAL INFORMATION.

BATTERY REQUIREMENTS. Batteries for FAA alternative energy applications generally would have the following requirements:

1. Deep discharge capability

2. Long cycle life

3. Fast recharge capability

4. Highly reliable with minimum preventive maintenance

5. Capable of operating satisfactorily in a wide range of environmental conditions

COMMERCIAL AVAILABILITY. Lead-acid batteries of all types are available from many sources. Several battery firms feature batteries specially adaptable or suitable for solar and wind-power storage. One manufacturer, C and D Batteries, Division of Eltra Company, located in Plymouth Meeting, Pennsylvania, features a selection of 2-V, lead-acid cells specifically adaptable for photovoltaic energy storage. These cells are available in capacities ranging from 40 to 3750 Ah at a 500 hour discharge rate. The lead in these cells is alloyed with a miniscule amount of calcium rather than the usual antimony. This prolongs the life of the electrodes, since the antimony normally used in other batteries would be electrochemically transferred from the cathode to the anode, poisoning the anode. The manufacturers offer a 5-year guarantee on these cells when used with a photovoltaic installation, with maintenence required but once each year.

Surrette Batteries of Tilton, New Hampshire, is a representative source of marine/industrial lead-acid batteries for use with wind generators. They are extra heavy duty deep-cycle batteries available in 12-V, 220-Ah units. Each battery measures 20.25 x 11 x 9.75 inches and weighs 170 pounds.

Nickel-cadmium batteries are likewise available from several sources. Two manufacturers who are involved in nickel-cadmium battery production are the General Electric Company, Battery Business Department, Gainesville, Florida and the Aero Quality Company, Teterboro, New Jersey.

AUXILIARY EQUIPMENT REQUIREMENTS. Voltage regulators may be required in conjunction with the battery output unless nickel-cadmium batteries, with their constant voltage characteristics, are used. Inverters or d.c.-to-d.c. converters may also be required if the equipment powered by the installation requires either a.c. or d.c. voltages which are higher than those produced by the batteries (appendix A).

INSTALLATION CONSIDERATIONS. Sufficient clearance should be provided in the battery mounting racks to permit ready access for maintenance purposes. Manufacturers' specifications should be consulted to determine if there are any temperature limitations imposed on the battery operation.

In lead-acid batteries, the higher the specific gravity of the electrolyte, the greater is the tolerance to cold weather. Therefore, if the batteries are to be operated in a cold region, a smaller depth of charge must be allowed than for a more temperate climate.

The physical orientation of the battery must also be considered. Wet cells must be mounted upright, but gelled electrolyte, or sealed batteries can be mounted in any position, since the electrolyte cannot spill.

In addition to the voltage and power requirements of the load which the battery supplies, the amount of Ah capacity required must be based upon the worst-case estimate of the time the battery may be required to furnish power without the benefit of being recharged from the photovoltaic calls or wind generator. A numerical example may make this clear. A repeater site in Navajo County, Arizona, uses photovoltaic cells to supply energy to a 150-W repeater. The electricity from the photovoltaic cells is stored in two 12-V, 500-Ah batteries. The energy contained in these two batteries is therefore 2x12x500, or 12,000-W hours. Assuming no losses, the energy in these two batteries should supply the repeater for 12,000 W-hours divided by 150 W, or 80 hours without benefit of recharge even under worst-case conditions. Allowing for losses etc., the batteries, when fully charged, would provide power for the repeater for a worst-case condition of about 3 days where insufficient insolation was available to recharge the batteries.

MAINTENANCE CONSIDERATIONS. Since there is no water loss, sealed batteries and gelled-electrolyte, lead-acid cells would require minimal maintenance. However, some of these batteries have vents for releasing gas, and these should be inspected occasionally to make sure they are not clogged. Wet cells require periodic checking of the electrolyete level and may require occasional additions of distilled water. Lead-calcium batteries rquire addition of water only once every 3 to 5 years, under average conditions. These batteries, when used in a photovoltaic system, require maintenance only once a year.

COST. A 2 V, 3750 Ah lead-calcium cell manufactured by the C and D Battery costs $324. The 12 V, 220 Ah battery manufactured by Surrette Battery Company costs $145, while a 12 V, 96-Ah Sears' Diehard® automotive-type battery costs $48.

Table 3 shows a comparison of costs for a 5-kW installation using three types of batteries: Surette, Eltra C and D, and Sears. This is based on worst-case discharge rates varying from 1 to 5 days. A 12-V battery output is assumed, which is changed to 115 V a.c. by an inverter. An 80 percent overall inverter efficiency is assumed; therefore, the batteries must supply 5000/0.8 or 6250 W. The batteries are assumed discharged to a 75-percent depth at the end of the discharge period. As an example, the cost of 6250 W of battery storage for a 3-day, worst-case discharge period would be $34,365 for the Surrette batteries, $27,216 for the Eltra C and D lead-calcium cells, and $26,064 for the automobile batteries. Battery costs for lower power requirements would be proportionately less. It is further noted that the cost for the automobile batteries, which were not designed for deep-discharge applications is almost the same as the cost for Eltra C and D cells which are specifically designed for this type application and for which a guarantee covering this application is available.

<u>SPECIFICATION CRITERIA</u>. Criteria to be considered an preparing specifications for battery procurement are listed.

1. Voltage, power, and ampere-hour ratings.

2. Contractually-specified and minimum-acceptable "mean time to failure" and "mean downtime".

3. Temperature.

4. Maximum physical dimensions and weight.

5. Preventive maintenance.

6. Depth of discharge.

7. Voltage regulation.

<u>SUMMARY</u>.

Storage batteries are an ideal medium for storing electrical energy generated by intermittent sources such as photovoltaic cells or wind-driven generators. Batteries operate because of a chemical reaction which occurs when two dissimilar materials (reactants) are placed in contact with an electrolyte. This chemical reaction changes the chemical energy stored in the battery into electrical energy, which is manifested by an electron flow from one of the reactants to the other through an external load. In the process of this energy change, the reactants are consumed or chemically changed into a different form.

In secondary cells, or storage batteries, the reactants are reversible. By forcing current through the battery in the opposite direction (charging), the electrical energy is converted into potential chemical energy by restoring the original (charged) form of reactants and electrolyte. It is this capability

TABLE 3. COMPARATIVE BATTERY CHART

6,250 Watts Battery Output (d.c.)
5,000 Watts Inverter Output (a.c.)
80 Percent Overall Inverter Efficiency
75 Percent Depth of Battery or Cell Discharge

Battery Type	Discharge Rate	Number of Units Required	Cost (Dollars)	Weight (Pounds)	Volume Feet[3] (Includes 2x2x24 inch Clearance Per Unit For Maintenance Access)
Surrette	5-Day	383	$55,535	65,110	1,498
Marine-	4-Day	310	44,950	52,700	1,213
Industrial	3-Day	237	34,365	40,290	927
12-Volt	2-Day	165	23,925	28,050	645
220-Ah	1-Day	92	13,340	15,640	360
Batteries					
Eltra C&D	5-Day	132	42,768	48,840	1,036
Lead-Calcium	4-Day	108	34,992	39,960	848
2-Volt	3-Day	84	27,216	31,080	659
3750-Ah	2-Day	60	19,440	22,200	576
Heavy Duty	1-Day	30	9,720	11,100	288
Cells					
Sears	5-Day	877	42,100	48,235	1,758
Diehard	4-Day	709	34,032	38,995	1,421
12-Volt	3-Day	543	26,064	29,865	1,088
96-Ah	2-Day	377	18,096	20,735	756
Automobile	1-Day	212	10,176	11,660	424
Batteries					

of being able to restore the chemical energy content by electrical charging which makes the secondary battery so well suited for storing electricity generated by photovoltaic cells and wind power for subsequent use when required.

Lead-acid batteries are the most common battery type in use today. They are available from many sources. Automobile-type batteries are relatively inexpensive but have a short life and poor depth of discharge characteristics. Industrial batteries have longer life, are more ruggedly built, and can be operated to greater depth of discharge than automobile batteries.

Several battery manufacturers design batteries specially adaptable for use with solar or wind generating systems. Among these are Surrette Battery Company, and C and D Battery Division of the Eltra Company.

There are many exotic high-energy-density batteries currently in the developmental stage. These include lithium-sulphide, nickel-hydrogen, sodium-sulphur, and other battery types. These exotic battery types have great potential for use at FAA remote sites, but they are not as yet economically feasible or technologically competitive with the more established lead-acid and nickel-cadmium types.

Batteries deliver relatively low d.c. voltages. Many equipment require higher a.c. voltages, such as 120 V 60 Hz. Inverters are used to convert the lower d.c. voltage from the battery into the required a.c. The inverters are chiefly solid-state devices operating as oscillators, in which the frequency of oscillation is determined by the characteristics of a saturable transformer. In other cases, high d.c. voltages, or perhaps merely isolation from the source is required. In such cases, d.c.-to-d.c. converters are used. These may be rotating machinery types or may incorporate vibrators, choppers, or solid-state electronic circuitry to convert the low-voltage d.c. from the battery into a.c. Full-wave or bridge rectifiers then reconvert the a.c. into the required d.c. voltage.

In both inverters and d.c.-to-d.c. converters, voltage regulation circuitry is often incorporated in the design. They operate by comparing all or part of the output voltage against a reference, amplifying the difference or error signal, and applying it to a regulating element which will absorb the change, leaving the output voltage relatively constant. Voltage regulation circuitry will often provide regulation to within a fraction of 1 percent against line or load variations.

COST CONSIDERATIONS OF ALTERNATIVE ENERGY SYSTEMS

GENERAL.

Photovoltaic, wind, fuel cell, and thermoelectric energy systems should be compared with regard to overall costs. It is essential that the system life cycle costs be determined, not just the initial purchase price of the alterna-

tive energy system. Therefore, applicable cost items such as basic hardware, storage capability, auxiliary hardware, transportation, installation, maintenance, and fuel are considered.

PHOTOVOLTAIC ENERGY SYSTEM.

Some manufacturers of solar photovoltaic arrays have their product costs listed on the General Services Administration (GSA) schedule. Prices per unit decrease as quantity order size increases. Prices and power ratings are based upon peak wattage rather than on continuous wattage. Since most of the FAA facilities utilization is on a continuous basis, one must multiply the peak wattage by a factor which is dependent upon the solar insolation data for a particular site location. The lower values are for locations where the sunshine days per year are high and the frequency of cloud, fog, or dust obscuring the sun is low. The converse is true for the higher values. Present prices are approximately \$13 a peak watt for the cells, \$4 per peak watt for the mounting hardware and power conditioning, and \$5 per peak watt for the battery storage. For purposes of comparison, transportation and installation costs are estimated to be \$500 each. Maintenance costs are considered to be minimal since only an annual cleaning of the array surfaces and perhaps a routine check of the batteries, etc. is all that is required. Therefore, maintenance is estimated at \$500 for the first year. No fuel costs are involved since the fuel in this case is provided by the sun.

An example of the cost per kilowatt-hour for a typical small photovoltaic system based upon a 10-year life is as follows. A marker beacon station requiring 26 continuous watts of power will be used as the example. It is assumed that the peak power to continuous power ratio is six which means a 156-watt array would be required. The *initial cost* to provide this power system would be:

156x\$13	=	\$2028	Cell Array
156x\$4	=	624	Mounting Hardware
156x\$5	=	780	Batteries, etc.
		500	Transportation
		500	Installation
		\$4432	Total System Cost

Assuming a system life of 10 years and assuming this money could otherwise be invested at between 7 and 8 percent; the capital investment would approximately double in 10 years for a total investment of \$8864. If it is also assumed that the estimated maintenance cost (\$500) will increase about 5 percent per year due to inflation etc., over the 10-year period, the cost including maintenance would be: \$8864 + \$6289 = \$15,153. Since the system is required to deliver 26 watts continuously, and there are 8760 hours in a year, the total power to be delivered over the 10-year period would be: 26 watts x 8760 hours x 10 years = 2,278 kilowatt-hours. The cost per kilowatt-hour would then be:

$$\text{Cost/kilowatt-hour} = \frac{15,153}{2,278} = \$6.65$$

WIND ENERGY SYSTEM.

Wind systems are particularly applicable in areas where wind power is reasonably large and the wind patterns are consistent, such as on mountain tops and along coast lines. Since winds do not normally blow continuously, a wind energy system must be properly sized. For a continuous load, a wind energy system must be 5 to 10 times the rated size of the system. This means that a 2-kW turbine could support a continuous load of 200 to 400 watts.

Costs for commercially available wind turbines vary with rated power output. For instance, a 2-kW wind turbine would cost about $3,000. Since a turbine must be supported above the ground by a tower or other structure, a 60 foot steel structure for the above turbine would cost about $1,000. Since winds are intermittent, some means must be provided for energy storage, which currently would be storage batteries. An estimate for batteries and power conditioning equipment for the above turbine would be $5,000. Transportation costs for this system are estimated at $1,000, while installation costs are estimated at $2,000. Inasmuch as periodic maintenance will be required, this may involve a few hours to a few days depending upon the magnitude of the repair. Therefore, maintenance is estimated at $1,000 for the first year. Once again no fuel costs are involved since fuel is provided by the wind.

An example of the cost per kilowatt-hour for a typical small wind energy system based upon a 10-year life is as follows: a weather rotating beam ceilometer requiring 200 continuous watts of a.c. power will be used as an example. To handle this load, the 2 kW wind energy system described above will be used. The system cost including turbine, tower, batteries, inverter, etc., transportation and installation, would cost about $12,000. Assuming a system life of 10 years and assuming this money could be otherwise invested as described under photovoltaics, the capital investment would be $24,000. Also assuming a 5-percent increase per year in maintenance costs, the total estimated cost of maintenance over the period would be $12,578. Therefore, the total cost of the system over the 10-year period would be: $24,000 + $12,578 = $36,578. Since the system is required to deliver 200 watts continuously, the total power delivered over the period would be: 200 watts x 8,760 hours x 10 years = 17,520 kilowatt-hours. The cost per kilowatt-hour would then be:

$$\text{Cost/kilowatt-hour} = \frac{\$36,578}{17,520} = \$2.09$$

THERMOELECTRIC GENERATORS.

The cost for fuel to operate a thermoelectric generator is a significant cost item in the life cycle of this system. As before, it is assumed that the system has a 10-year life. A 36-W, 24 V thermoelectric generator costs $2,180. Once again, assuming this money could otherwise be invested and would double over the 10-year period, the total investment would be $4,360. The propane fuel required to operate this unit is 44.8 pounds per week or 2,330 pounds per year. Since propane can be purchased for about $0.15 per pound, it would cost about $350 for the first year. Assuming the cost of fuel will increase

10 percent per year during the next 10 years, the total cost of fuel over the 10-year period would be $5,578. Transportation and installation costs are estimated to be $500 each, while the cost of maintenance is estimated at $500 for the first year. Assuming the cost of maintenance will increase at the rate of 5 percent per year, the total cost of maintenance over the 10-year period would be $6,289. Therefore, the total cost of the system over the 10-year period would be: $4,360 + $5,578 + $500 + $500 + $6,289 = $17,227. Since the system will deliver 36 W continuous power, the total power delivered over the 10-year period would be: 36 W x 8,760 hours x 10 years = 3,154 kWh. The cost per kWh would then be:

$$\text{Cost/kilowatt-hour} - \frac{\$17,227}{3,154} = \$5.46$$

FUEL CELLS.

The U.S. Army in 1976 estimated that a 1.5 kW fuel cell now under development with associated inverter would cost about $3,000 in production quantities. Using the 1.5 kW fuel cell as an example, and assuming it will not be available on a production basis until 1980, the potential cost per kilowatt-hour during the 1980-1990 time period can be projected. This is based upon a 10-year life and a 1980 cost estimate of $3,500 for the fuel cell. As before, if this amount could otherwise be invested, it would double over the 10-year period for a total investment of $7,000. Transportation and installation in 1980 are estimated at $1,000 each while maintenance is estimated at $1,000 per year. Assuming the cost of maintenance will increase at the rate of 5 percent per year, the total cost of maintenance would be $12,578. Fuel costs are estimated to be $15,000 the first year with the cost increasing at the rate of 10 percent per year, giving a total cost of fuel of $239,061. Therefore, the total cost of the system over the 10-year period would be: $7,000 + $1,000 + $1,000 + $12,578 + $239,061 = $260,639. Since the system will deliver 1.5 kW continuous power, the total power delivered over the 10-year period would be: 1.5 kW x 8,760 hours x 10 years = 131,400 kWh. The cost per kilowatt-hour would then be:

$$\text{Cost/kilowatt-hour} = \frac{\$260,639}{131,400} = \$1.98$$

SUMMARY.

The cost per kilowatt-hour for power from solar photovoltaic, wind, thermoelectric generators and fuel cells has been estimated. The fuel cell offers potential cost advantages over these other sources. However, they are not yet commercially available and require fuel, which is a significant cost item.

On the other hand, solar photovoltaic and wind energy systems do not need an outside source of fuel. Wind energy systems show cost advantages over the photovoltaic energy system and the thermoelectric generator. The cost of the photovoltaic and thermoelectric generator systems is currently in the same range. However, the photovoltaic system does not require fuel and could be more economical than the thermoelectric generator system during the coming

decade. Looking into the future, it is believed the photovoltaic and wind energy systems will one day be competitive.

A search for competitive nonfossil fuels for use in fuel cells is considered essential and a fuel processor versatile enough to process a variety of fuels appears highly desirable. Furthermore, since the potential for fuel cells is encouraging, research, development, and demonstration programs should be accelerated.

ENERGY REQUIREMENTS AND POTENTIAL CANDIDATE SITES FOR ALTERNATIVE ENERGY SYSTEMS

GENERAL.

The FAA has many different types of facilities with thousands located throughout the contiguous United States, and in the Alaskan and Pacific Regions. A partial listing of FAA facilities and their complement is contained in table 4. As indicated, there are hundreds of remote center air/ground communications facilities, radar microwave links, nondirectional beacons and instrument landing systems (including glide slopes, localizers, and marker beacons). The power consumption of these facilities range from less than 100 W to a megawatt or more. Many of these facilities are remote, unattended, and inaccessible during certain periods of the year, making it difficult to deliver fuel, etc; while at the same time the facility may be critical to FAA operations.

An essential imput to any life cycle cost analysis for an alternative energy system is the actual power requirement of the facility. Short of physically measuring the power consumption, accurate and complete information is difficult to obtain. Actual power consumption data is probably available but quite dispersed, and even when accessible it is difficult to interpret due to fluctuations of the data from one month to the next. Although transformer ratings and/or backup generator ratings are available, they cannot be utilized to make definitive conclusions on power due to the fact that these ratings are usually much higher than the actual facility power requirement.

Another essential consideration which will affect any life cycle cost analysis is the existance or nonexistance of reliable commercial power. If commercial power is not currently available, or if it is available but unreliable, such a facility would at least initially become a prime candidate for some type of alternative power. In addition, planned facilities where commercial power is not currently available would also fall into the category of being a prime candidate for application of alternative power.

FAA ENERGY REQUIREMENTS.

Although our investigation into the availability of FAA facility power consumption data was limited, there does not exist within the FAA a centralized collection and tabulation point where data of this type can be obtained. However, the regions usually do maintain some data of this type, but it varies

TABLE 4. PARTIAL LISTING OF FAA FACILITIES

Facility	Total Complement
Centers	25(A)
ARSR (Air Route Surveillance Radar)	99
RCAG (Remote Center A/G Sites)	470
VOR/VORTAC (All Combinations)	1021(B)
Nondirectional Beacons	881(C)
Towers	481(D)
CS/T (Combined Station/Tower)	21
ASR (Airport Surveillance Radar)	172(E)
RAPCON/PATCF (Military Radar)	26
ILS (Instrument Landing System)	605(F)
FSS (Flight Service Stations)	322
IFSS (International Flight Service Stations)	7
RCO (Remote Communications Outlets)	40
DOP/DF (Doppler Direction Finder)	155
RMLT (Radar Microwave Link - Terminal)	218
RMLR (Radar Microwave Link - Repeater)	127

(A) Includes 2 CERAPS.
(B) Includes 65 non-federal and 49 military.
(C) Includes 523 non-federal and 68 military.
(D) Includes 29 non-federal and 47 military.
(E) Includes 31 military.
(F) Includes 5 LDA's, 39 non-federal and 7 military.

quite widely from computer printout summarization data for the entire region to actual vouchers for electric service for specific facilities. Some of these data indicate wide fluctuations from month to month and even no apparent readings during a specific month. This makes it very difficult to interpret the data and adds weight to the general view that each potential facility should be studied and an alternative energy system designed to meet the needs of a specific facility. Although it was not possible to secure data from all regions, some data were obtained and used to determine power consumption for several different types of facilities.

The results of a partial examination of power consumption data for FAA facilities in the Southwest Region is contained in table 5. The number of facilities within selected power ranges are shown, e.g. seven air route surveillance radars (ARSR) have power requirements of 51 to 100 kW. Note that the only facility type shown that has a power requirement above 150 kW is the air route traffic control center (ARTCC) with the majority of the facilities requiring less than 10 kW.

Table 6 lists power consumption data for several Rocky Mountain Region facilities located in Colorado. Power consumption is in kilowatt-hours and is given for each month. Power consumption data in computer printout form for the Eastern and New England Regions were obtained from the regional offices. Data for the period October 1976 through September 1977, including quantity and cost of power consumed for a number of facility types at various locations, were extracted from these printouts and are contained in appendix C. As a point of general interest, the printout data also indicated that during this one year period the Eastern Region consumed a total of 73,198,444 kW-hours at a cost of $2,660,974 while the New England Region consumed a total of 24,710,529 kW-hours at a cost of $778,748.

Of particular interest in the design and application of alternative energy systems is the maximum usage as well as the average usage. Although not reflected in this data, but nevertheless important, is a further breakdown of power consumed, such as power used for the electronic equipment only, (it could be possible to use an alterntative power source for just the electronic equipment) such as heaters, air conditioners, blowers, etc. The need for power consuming equipment other than the electronic system itself should be verified and justified, since in terms of power consumed, these can be very costly items.

FAA POTENTIAL CANDIDATE SITES.

In order to identify potential FAA facilities where it might be feasible and cost effective to use an alternative energy system, two questionnaires were developed. One was directed toward facilities that are still in the planning stages, while the other questionnaire was developed for existing facilities.

PLANNED FACILITIES. It is certainly more desirable and generally more cost effective to plan and system design a facility with the thought of utilizing an alternative energy system than it is to retrofit an existing facility that currently has adequate commercial power available. The extension of commercial

TABLE 5. A PARTIAL LISTING OF SOUTHWEST REGION FACILITIES AND THEIR ELECTRICAL POWER REQUIREMENTS BY RANGES OF VALUES IN KILOWATTS (12-21-76)

Facility Type	Number of Facilities using the following Power Ranges (Kilowatts)								
	1	1-10	11-25	26-50	51-100	101-150	151-500	501-1000	1000
AFS	1	1							
ALS		13	2						
ARSR		1	1		7	1			
ARTCC								1	2
ASR		1	5	3					
ATCT	1	4	7	4	1	1			
BEACON SITE	2								
CS/T		3	1						
FMAP	1	1							
FPS					1				
FSS		10	9						
GS		5	1						
HIALS		1							
LOC	2	19	1						
MALS	1								
MALSR		1							
MM	14	12							
NAVAIDS SW SUBSTATION			4						
OM	25	12							
PERIPHERAL		20	1						
RBC	1								
RCAG	1	15							
REIL	2								
RMLR		42	1						
RTR	4	32	6	1					
SFO		2							
TVOR		11							
VASI		7							
VOR		5	10	2					
VORTAC		4	48	11					
TOTAL	54	221	97	21	9	2		1	2

TABLE 6. SOME ROCKY MOUNTAIN FACILITIES AND THEIR ELECTRICAL POWER REQUIREMENTS

A. RUNWAY END IDENTIFICATION LIGHTING (REIL), MONTROSE, COLORADO

December 1974	310
February 1974	290
April 1974	230
June 1974	220

B. TERMINAL VHR OMNIRANGE (TVOR), MONTROSE, COLORADO

July 1974	1980
August 1974	2120
September 1974	1960
October 1974	2310
November 1974	2210
December 1974	3029
January 1975	3541
February 1975	3170
March 1975	2510
April 1975	1930
May 1975	2120
June 1975	1840

C. REMOTE CENTER AIR/GROUND COMMUNICATIONS (RCAG) EAST, GRAND MESA, COLORADO

May 1974	4340
June 1974	2030
July 1974	2220
August 1974	2310
September 1974	3350
October 1974	3700
November 1974	4000
December 1974	4000
January 1975	4990
February 1975	5000
March 1975	4900
April 1975	4200

D. REMOTE CENTER AIR/GROUND COMMUNICATIONS (RCAG) WEST, GRAND MESA, COLORADO

Date	kWh
May 1974	360
June 1974	4909
July 1974	5279
August 1974	5238
September 1974	5067
October 1974	5000
November 1974	5000
December 1974	4500
January 1975	6000
February 1975	5500
March 1975	5000
April 1975	4000

E. FLIGHT SERVICE STATION (FSS), LaJUNTA, COLORADO

August 1974	5483
September 1974	7858
October 1974	3924
November 1974	4892
December 1974	4043
January 1975	4829
February 1975	4776
March 1975	3893
April 1975	4737
May 1975	4467
June 1975	5832
July 1975	7700
August 1975	8400

F. AIR ROUTE SURVEILLANCE RADAR (ARSR), GRAND JUNCTION, COLORADO

January 1974	38400
February 1974	38000
March 1974	40080
April 1974	40000
May 1974	35720
June 1974	37360
July 1974	25080
August 1974	35240
September 1974	29680
October 1974	38520
November 1974	25240
December 1974	44160
January 1975	48560
February 1975	24840
March 1975	41960
April 1975	45040
May 1975	30920
June 1975	31440
July 1975	32640

power lines can be an expensive undertaking and even cost prohibitive depending on the distance and the type of terrain. If an alternative energy system could be utilized, site selection can be flexible and can be optimized without concern for availability of commercial power. In addition, by being able to system design the complete facility, it is possible to ensure the use of energy efficient devices and to specify wide ranges of environmental operating conditions so that heating and/or cooling can be minimized or eliminated.

The questionnaire concerning planned facilities was sent to each region headquarters and to each airway facilities division in Washington, D.C., asking that planned facilities where commercial power may not be available and where alternative power (solar photovoltaics, wind, fuel cells, etc.) might have application, be identified. The results from those who responded to the questionnaire are summarized in table 7.

Firm plans have already been made to establish a marker beacon (MB) at Springfield, Missouri with power to be provided by a solar photovoltaic system; tentative plans have also been formulated to use a wind energy conversion system to provide power to a MB scheduled for installation at Colby, Kansas. Another MB site at Kenai, Alaska has been utilizing a solar photovaltaic system for more than a year. However, this application has not been completely successful with many problems being experienced. Of course the difficult environmental conditions and the extreme range of the diurnal cycle in Alaska makes the successful use of a solar photovoltaic system a challenging task. As seen in table 7, as far as the future is concerned, the moving target indicator (MTI) reflector looks like an ideal candidate. It is low power, the optimum locations for installation may not have commercial power available, and the 1980 planned installation period provides an adequate lead time to complete an overall system design that will ensure properly integrated alternative power. In this case a solar photovoltaic power system seems like a logical solution. Although apparently a one of a kind application, the beacon transponders (general aviation type transponder) which the Western Region uses for radar certification could also be adapted quite easily to use a solar photovoltaic power system. Region personnel indicate that the most desirable locations for these transponders are without commercial power. The marker/compass locator (MCOML) and single frequency outlets (SFO) listed in table 7 are all prime candidates for some type of alternative power system. However, considering the planned installation date, the MBS at Sioux Falls, Salt Lake City, and Colorado Springs would probably be most practical since sufficient time is available to accomplish the system design and power integration effort. Of the planned facilities having high-power requirements that are listed in the table 7, only the facility at Umiat, Alaska has a lead time (1980) that would provide sufficient time to properly investigate the availability of an alternative power system that could provide the necessary power.

EXISTING FACILITIES. In an effort to determine the existence of operational facilities that could be potential candidates for an alternative power system. a questionnaire was developed and sent to each of the FAA sector field offices plus the sector offices in Hawaii and Guam. The rationale was to offer an easily commpleted questionnaire and to direct it to the level having close responsibility for maintenance. From a total 414 questionnaires sent, 310 replies were received for a percent return rate.

TABLE 7. PLANNED FAA FACILITIES WITH POTENTIAL FOR ALTERNATIVE POWER SYSTEM

Facility Type	Planned Location	Estimated Total Power Requested	Planned Installation Date	Remarks
MTI Reflector	Various Locations	<1 W	1980	Being planned by AAF-300 (Wash.). Commercial power not practical in many desired locations.
Beacon Transponder	Various locations (Western Region)	28 W	Current	Used as radar/computer certification fix. Desired location and availability of commercial power in many cases do not coinside.
MB	Springfield, Mo.	24 W	4/78	Solar photovoltaic system will be the primary power source.
MB	Colby, KS	24 W	5/79	In planning stage - Wind energy system being considered as primary power source.
MB	Sitka, AK	26 W	10/78	Available commercial power is located 3 1/2 miles across body of water.
SFO	Owhyee, NV	30 W	6/78	Decision on power will be made by May 1978.
SFO	Jackpot, NV	30 W	6/78	Decision on power will be made by May 1978.
SSO	Alsek River, AK	20-50 W	10/78	Current plans are to use thermoelectric generator as primary power source.
MB	Sioux Falls, DS	100 W	9/79	---
MB	Salt Lake City, UT	100 W	10/79	---
MB	Colorado Springs, CO	100 W	10/79	---
MCOML	Billings, MT	150 W	6/78	---
SFO	Helena, MT	650 W	7/78	---
SFO	Judith Gap, MT	650 W	9/78	---
SFO	Leadville, CO	650 W	9/78	---
VOR/DME/RCAG/ LCOT	Umiat, AK	20 kW	1980	Current plans are to use dual diesel generators as primary/ backup power source. Fueled by helicopter from Deadhorse (distance 120 miles). Facility heated and cooled.
RCAG	Mt. Humboldt, AZ	25 kW	10/78	Decision on power will be made by May 1978. Facility heated and cooled.
VOR/TACAN	Lake Tahoe, CA	30 kW	8/78	Decision on power will made by January 1978. Facility heated and cooled.
VOR/TACAN	Susanville, CA	30 kW	8/78	Decision on power will be made by March 1978. Facility heated and cooled.

The questionnaire was to identify field facilities that could be considered potential candidates for alternative power with the idea that further in depth investigation would ultimately be required before any definite decisions could be finalized. To accomplish this initial effort, three categories of facilities were established: Facilities that (1) currently use an engine generator for primary power, (2) have unreliable commercial power resulting in an abnormal number of power outages during a year, and (3) may be difficult to access or may be completely inaccessible at times of the year. Out of 313 replies that were received, 73 answered in the affirmative indicating they had a facility or facilities that fell within one or more of the categories.

Of the three categories, the one that offers the most potential for cost saving by switching to an alternative form of power would be those facilities utilizing an engine generator for primary power. Power produced in this manner is very costly; therefore, the potential for being cost effective is the greatest. From the questionnaire, and based upon those responding, facilities currently using engine generators for primary power are listed in table 8. This table shows that the estimated power requirements for those facilities vary from a low of 6 kW to a high of 175 kW. Due to these relatively high power requirements, solar photovoltaics are virtually eliminated on the basis of cost, leaving only the possibility of wind energy systems or fuel cells. When commercially available, fuel cells will probably be the most effective power source for most all of these facilities with a wind energy system being a possibility only in the lower power ranges (10 kW) and only in those locations where sufficient winds are available. Each of the 14 facilities should be studied further in order to determine the best alternative power system for that specific location.

The second category for facilities that may have potential for utilizing alternative power are those that have unreliable commercial power, resulting in an abnormal number of power outages each year. These outages can represent a serious problem depending on how often outages occur, how long they last, and whether an adequate backup power source is available, which may justify an alternative power system. Based upon those responding to the questionnaire, a total of 184 facilities are listed in table 9 as having unreliable commercial service with over half of these facilities not having a backup power source. The facilities reported varying power requirements from a low of approximately 24 W for a MB to a high of 300 kW for a long-range radar facility. Based on power only, with other conditions being satisfied, general guidelines from the literature seem to indicate that solar photovoltaics should be considered in low-power applications (less than 1 kW continuous), wind systems should be considered up through medium-power applications (less than 10 kW continuous), and that fuel cells should be considered in the medium- to high-power applications (from 1 kW to greater than 10 kW continuous). There are always exceptions based upon a specific application, but these guidelines do provide a reasonable starting point.

Time did not permit further detailed investigation of the data compiled in table 9. However, the next logical step would be to select several facilities that seem to meet the power limitations for a specific alternative power system

TABLE 8. EXISTING FAA FACILITIES USING ENGINE GENERATORS FOR PRIME POWER

Facility Type	Location	Estimated Total Power Requirement
NDB	Chandalar, AK	6 kW
RMLR	Antelope Gap, WY	10 kW
RMLR	Pine Ridge, WY	10 kW
HH	Bimini, Bahamas	10 kW
RCO/H	Summit, AK	12 kW
RCAG	Firndale, CA	15 kW
VOR/NDB	Moses Point, AK	20 kW
RCAG	Ukiah, CA	25 kVA
VOR/TACAN	Douglas, WY	28 kW
Equip Garage	Battle Mt, NV	30 kW
VORTAC	Bimini, Bahamas	34 kW
VORTAC	Ukiah, CA	37 kVA
ARSR	Lusk, WY	110 kW
ARSR	Mt. Laquna, CA	175 kW

TABLE 9. EXISTING FAA FACILITIES WITH UNRELIABLE COMMERCIAL POWER

Facility Type	Location	Estimated Power Requirement Electronic Equipment Only	Total Facility	Backup Power
OM	Franklin, PA	24 W	24 W	Battery
OM	Jamestown, PA	24 W	24 W	Battery
OM	State College, PA	24 W	24 W	Battery
OM	Marquette, MI	--	48 W	Battery
OM	Mosinee, WI	--	48 W	Battery
OM	Houghton, MI	--	283 W	Battery
OM	Iron Mt., MI	48 W	4 kW	Battery
OM	Loudoun County, VA	125 W	1.8 kW	None
OM	Ft. Lauderdale, FL	180 W	180 W	Battery
OM	Mobile, AL	180 W	1.9 kW	None
OM	Agana, Guam	190 W	300 W	Battery
OM	Mobile, AL	1.3 kW	5.6 kW	None
OM (32L)	Omaha, NE	--	--	None
OM (14R)	Omaha, NE			EG
OM	Lincoln, NE	--	--	None
MM	Franklin, PA	24 W	24 W	Battery
MM	Jamestown, PA	24 W	24 W	Battery
MM	State College, PA	24 W	24 W	Battery
MM	Marquette, MI	--	48 W	Battery
MM	Mosinee, WI	--	48 W	Battery
MM	Houghtonn, MI	--	108 W	Battery
MM	Iron Mt. MI	48 W	4 kW	Battery
MM	Agana, Guam	190 W	300 W	Battery
MM	Alexandria, LA	200 W	250 W	None
MM	Ft. Laurderdale, FL	200 W	320 W	Battery
MM	Sioux City, IA	211 W	400 W	None
MM	Mobile, AL	312 W	4.4 kW	None
MM	Longview, TX	1.3 kW	5.3 kW	None
MM	Savannah, GA	1.5 kW	3.5 kW	None
MM (32L)	Omaha, NE	--	--	Battery
MM (32R)	Omaha, NE	--	--	Battery
MM	Lincoln, NE	--	--	None
FM	Norfolk, NE	--	--	None
LOM	Redding, CA	150 W	1.2 kW	None
LOM	Jackson, TN	500 W	1 kW	None
LOM	Longview, TX	2.2 kW	7.2 kW	None
OM/LOM	Savannah, GA	4 kW	6 kW	None
OM/LOM*	Lafayette, IN	2.1 kW	4.5 kW	None
OM/LOM	Evansville, IN	1 kW	5 kW	None
OM/LOM	Sioux City, IO	580 W	800 W	None
MM/LOM*	San Franxisco Bay, CA	600 W	3.5 kW	EG
LRCO	Redding, CA	100 W	1.2 kW	None
LRCO	Chico, CA	100 W	1.2 kW	None
H	Jackson, NE	630 W	750 W	None
H	Vinton, VA	800 W	8 kW	None
H	Montague, CA	1 kW	5 kW	None
H	Proberta, CA	1 kW	5 kW	None
H	Columbus, NE	--	--	None
HH	Talofofo, Guam	20 kW	25 kW	EG

TABLE 9. EXISTING FAA FACILITIES WITH UNRELIABLE COMMERCIAL POWER (Continued)

Facility Type	Location	Estimated Power Requirement: Electronic Equipment Only	Total Facility	Backup Power
SFO	Santa Rosa, CA	100 W	1.6 kW	None
SFO	Ukiah, CA	100 W	1.6 kW	None
SFO	Quincy, CA	100 W	1.6 kW	None
SFO	Fall River Mills, CA	100 W	1.6 kW	None
SFO	Dark Canyon Ridge/ Carlsbad, NM	1.8 kW	1.8 kW	None
RMLR*	Holston Mt., TN	1.2 kW	14.4 kW	EG
RMLT	Sn Rosa, Guam	2 kVA	--	EG
RMLR*	Iron Mt., UT	2 kVA	6 kVA	EG (Gas)
RMLR*	Big Mt., UT	2 kVA	6 kVA	EG (Diesel)
RMLR	San Carlos, AZ	4 kW	5 kW	EG
RMLR	Pina, AZ	4 kW	5 kW	EG
RMLR	Stafford, AZ	4 kW	5 kW	EG
RMLR*	Lamoille Summet, NV	13 kW	18 kW	EG (Gas)
VOR	Chico, CA	1 kW	4 kW	None
VOR	Redding, CA	1 kW	4 kW	None
VOR	Santa Rosa, CA	1 kW	8 kW	None
VOR	Jackson, TN	2 kW	5 kW	None
VOR	Harrison, AR	2.5 kW	3.5 kW	None
VOR	Fayetteville, AR	2.5 kW	3.5 kW	None
VOR	Worthington, MN	6 kW	6 kW	None
VOR	Albany, GA	14.5 kW	21.6 kW	None
VOR	Cody, WY	18 kVA	18 kVA	None
DME	Homer, AK	--	--	None
VOR/DME/ RRH	Ft. Lauderdale, FL	3.2 kW	9 kW	None
VOR/DME	Fairmont, MN	6 kW	6 kW	None
VOR/DME	Mankato, MN	6 kW	6 kW	None
VOR/DME	Hayden, CO	--	--	None
VOR/LRCO	Lima, OH	--	--	None
VOR/TACR	Carlsbad, NM	25.8 kW	28 kW	None
VORTAC	Deming, NM	15 kW	20 kW	None
VORTAC	Douglas, AZ	17.6 kW	22 kW	EG
VORTAC*	Sault St. Marie, MI	18 kW	25 kW	EG
VORTAC*	Pellston, MI	18 kW	25 kW	EG
VORTAC	Columbus, NM	20 kW	25 kW	EG (Gas)
VORTAC	Hill City, KS	20 kW	29 kW	EG
VORTAC*	Richmountain, OK	21 kW	35 kW	EG (Gas)
VORTAC	Macon, MO	22 kW	37 kW	None
VORTAC*	Lafayette, IN	23.4 kW	26.3 kW	EG
VORTAC	San Simon, AZ	24 kW	30 kW	EG
VORTAC	Cochise, AZ	24 kW	30 kW	EG
VORTAC	White Lake, LA	25 kW	30 kW	EG (Gas)
VORTAC*	Lamoille Summet, NV	25 kW	30 kW	EG (Diesel)
VORTAC	Reno, NV	25 kW	50 kW	EG (Diesel)
VORTAC*	Lake Tahoe, NV	25 kW	50 kW	EG (Diesel)
VORTAC*	Williamsport, PA	26 kW	29 kW	EG
VORTAC	Thurman, CO	29 kW	29 kW	None
VORTAC*	Boysen Peak, NY	30 kVA	65 kVA	EG (Diesel)
VORTAC*	Holston Mt., TN	32 kW	40 kW	EG
VORTAC	Agana, Guam	40 kW	58.5 kW	EG
VORTAC	Lincoln, NE	--	--	EG
VORTAC	Tuscaloosa, AL	--	--	EG

TABLE 9. EXISTING FAA FACILITIES WITH UNRELIABLE COMMERCIAL POWER (Continued)

Facility Type	Location	Estimated Power Requirement: Electronic Equipment Only	Estimated Power Requirement: Total Facility	Backup Power
GS	Franklin, PA	72 W	2 kW	Battery
GS	Jamestown, PA	72 W	2 kW	Battery
GS	State College, PA	72 W	2 kW	Battery
GS	Crescent City, CA	150 W	1.2 kW	None
GS	Santa Rosa, CA	150 W	1.2 kW	None
GS	Ft. Lauderdale, FL	264 W	2.9 kW	None
GS	Mosinee, WI	323 W	10 kW	None
GS	Marquette, MI	323 W	10 kW	None
GS	Iron Mt., MI	323 W	10 kW	None
GS	Agana, Guam	350 W	4.8 kW	UPS
GS	Gainesville, FL	350 W	13 kW	None
GS	Hattiesburg, MS	350 W	15 kW	None
GS	Houghton, MI	400 W	530 W	None
GS	Alexandria, LA	450 W	1.5 kW	None
GS	Santa Maria, CA	900 W	2 kW	None
GS**	Escanaba, MI	1 kW	3.9 kW	None
LOC	Franklin, PA	120 W	2 kW	Battery
LOC	Jamestown, PA	120 W	2 kW	Battery
LOC	State College, PA	120 W	2 kW	Battery
LOC	Santa Rosa, CA	150 W	1.2 kW	None
LOC	Redding, CA	150 W	1.2 kW	None
LOC	Crescent City, CA	150 W	1.2 kW	None
LOC	Agana, Guam	350 W	5.8 kW	UPS
LOC	Jackson, TN	350 W	7.5 kW	None
LOC	Hattiesburg, MS	350 W	15 kW	None
LOC	Gainesville, FL	350 W	18 kW	None
LOC	Ft. Lauderdale, FL	360 W	2.9 kW	EG
LOC	Marquette, MI	385 W	9.8 kW	None
LOC	Mosinee, WI	385 W	9.8 kW	None
LOC	Iron Mt., MI	385 W	9.8 kW	None
LOC	Houghton, MI	400 W	7.4 kW	None
LOC	Alexandria, LA	450 W	1.5 kW	None
LOC	Atlanta, GA	780 W	1.7 kW	None
LOC	Escanaba, MI	1.5 kW	9.5 kW	None
LOC	Santa Maria, CA	1.9 kW	6.7 kW	None
LOC	Pellston, MI	8 kW	12 kW	None
LOC	Homer, AK	--	--	None
RTR	Ukiah, CA	1.5 kW	2 kW	None
RTR	Red Bluff, CA	1.5 kW	2 kW	None
RTR/Rx	Andersen AFB, Guam	--	6 kW	EG
RTR/Tx	Andersen AFB, Guam	--	12 kW	EG
RTR*	Reno, NV	14 kW	20 kW	EG (Diesel)
RCAG	Animas, NM	--	10 kW	EG (Gas)
RCAG/Rx	San Rosa, Guam	3 kW	20 kVA	EG
RCAG*	Reno, NV	15 kW	20 kW	EG (Diesel)
RCAG*	Elko, NV	15 kW	20 kW	EG (Diesel)
RCAG/Tx/ IFST/LCOT	San Rosa, Guam	--	100 kW	EG
ALS	Savannah, GA	100 kW	100 kW	None
MALS	Homer, AK	--	--	None
MALS	Santa Rosa, CA	--	9 kW	None

TABLE 9. EXISTING FAA FACILITIES WITH UNRELIABLE COMMERCIAL POWER (Continued)

Facility Type	Location	Estimated Power Requirement: Electronic Equipment Only	Estimated Power Requirement: Total Facility	Backup Power
MALSR	Alexandria, LA	7.5 kW	7.5 kW	None
MALSR	Crescent City, CA	--	9 kW	None
MALSR	Redding, CA	--	9 kW	None
MALSR	Jackson, TN	15 kW	18 kW	None
REIL	Ukiah, CA	--	2 kW	None
SSALR	Longview, TX	--	25 kW	None
VASI	Ukiah, CA	--	3.5 kW	None
VASI	Red Bluff, CA	--	3.5 kW	None
VASI	Homer, AK	--	--	None
RBC	Ft. Lauderdale, FL	1.4 kW	1.4 kW	None
RBC	Santa Rosa, CA	2 kW	--	None
RBC	Napa, CA	2 kW	--	None
FSS	Montague, CA	3 kW	7 kW	None
FSS	Crescent City, CA	3 kW	8 kW	None
FSS	Ukiah, CA	3 kW	12 kW	None
FSS	Marysville, CA	3 kW	12 kW	None
FSS	Douglas, AZ	10 kW	10 kW	EG
IFSS	Finegayan, Guam	152 kW	271.5 kW	EG
PAR	Andersen AFB, Guam	--	24 kW	EG
ASR/ ATCRB	Andersen AFB, Guam	--	--	EG
ARSR	Apple Valley, MN	50 kW	70 kW	EG
ARSR*	Cedar City, UT	50 kVA	75 kVA	EG (Diesel)
ARSR*	Medicine Mt., WY	50 kVA	125 kVA	--
ARSR*	Island Park, ID	90 kVA	105 kVA	EG (Diesel)
ARSR	Santa Rosa, Guam	112.5 kVA	128.7 kVA	EG
ARSR	Red Rock Mt., PA	140 kW	200 kW	EG (Diesel)
ARSR	Mt. Kaala, Oahu, HI	--	300 kW	EG
ARSR	Humboldt Mt., AZ	--	--	EG
ARSR	Bucks Harbor, ME			EG (Diesel)
ATCRB	Santa Rosa, Guam	15 kW	--	EG
ATCT(FXE)	Ft. Lauderdale, FL	2 kW	26 kW	Battery
ATCT(HWO)	Ft. Lauderdale, FL	4 kW	43 kW	None
CERAP/ RBDE	Andersen AFB, Guam	37 kW	80 kW	EG
RRH	Santa Rosa, CA	500 W	--	None

*Facilities are difficult to access or inaccessible at times during the year.

**Not commissioned.

and then investigate each one to find out the details of power required, exact location, environmental conditions, etc. Another consideration is that since over half the reported facilities have no backup power source, it might be practical to implement an alternative power system as a backup to the existing commercial service. Then, when and if the alternative system proved adequate, it could be phased in as the primary power source with the commercial source assuming the backup position.

During the course of collecting the questionnaire data, telephone calls were received from several facilities. In some cases the calls involved facilities that have power problems that are apparently caused by the fact that commercial service is being supplied by a cooperative electric company; one who generates no electrical power itself but purchases all power from other utilities, and just handles distribution. The problem is that the co-op company does not provide a warning when commercial power is to be reduced or dropped. When the original utility experiences a load problem, the first area to be reduced or dropped is the co-op--word of this reduction or dropping either never reaches the user or it is never issued. As a result, the facility does get caught unexpectedly and at times without backup capability. This apparently happens often enough to be considered a problem at some facilities.

In the area of unreliable commercial power, another interesting situation exists at several long range radar sites. During the course of conducting grounding surveys, NAFEC personnel found that at Fallon and Battle Mountain, Nevada, and probably other sites in the western portion of the United States, serious commercial power fluctuations are experienced. These are generally caused by large load variations caused by such things as periodic power demands by mining operations, water pumping requirements, etc. To stabilize the power and thus correct the fluctuation problem, the facilities use the incoming commercial service to drive a motor generator, employing the output of the generator to supply the needs of the facility. Although this does correct the problem, it is a very inefficient solution, and with the increasing premium being placed on energy, it should be further investigated. Energy saving and/or improved efficiency could be realized at some future time either by use of an alternative power system or by some other means after the situation is thoroughly studied.

The third category of facilities are those that are difficult to access or are completely inaccessible during some periods of the year. These remotely located facilities can have occasional problems with commercial power, usually during extreme weather situations, and as a result the backup power system, engine generator or battery, is used. This means that fuel must be supplied, engine generator maintenance performed, or possibly batteries replaced; all difficult tasks when coupled with severe weather and remoteness of the location. There are 80 facilities reported as being in this category and these are listed in table 10. Power requirements for these facilities, as provided by the respondents, vary from a low of 50 W for a OM/LOM at West Yellowstone, Montana, to a high of 1600 kW at a new communications facility to be constructed starting in May 1978 at Judith Mountain, Montana. Because of the fact that commercial power is not readily available, the MB at West Yellowstone is currently being powered by a thermoelectric generator; however, it is only operational

TABLE 10. EXISTING FAA FACILITIES DIFFICULT TO ACCESS OR INACCESSIBLE DURING PERIODS OF THE YEAR

Facility Type	Location	Estimated Power Requirement: Electronic Equipment Only	Estimated Power Requirement: Total Facility	Backup Power
OM/LOM	West Yellowstone, MT	26 W	50 W	Battery
OM/LOM	Gainesville, FL	790 W	790 W	Battery
FM Repeator	Mt. Graham, AZ	500 W	500 W	None
H	Puntiua Lake, AK	1 kW	2 kW	EG
RMLR	Regina, NM	750 W	1.2 kW	EG
RMLR	Abiquiu, NM	750 W	1.2 kW	EG
RMLR	Lund, UT	1 kVA	6 kVA	EG (Gas)
RMLR	Bays Mt., TN	1.2 kW	14.4 kW	EG
RMLR	Newland, NC	1.2 kW	14.4 kW	EG
RMLR*	Buena Vista, VA	3 kW	11.6 kW	EG
RMLR	Montana Mt., NJ	4 kVA	5 kVA	EG (Gas)
RMLR	Mt. Freedon, NJ	4 kVA	5 kVA	EG (GAS)
RMLR	Questa, NM	4.8 kW	7.7 kW	EG
RMLR	Rowe Mesa, NM	6.1 kW	11.2 kW	EG
RMLR	Abiquiu, NM	9.2 kW	11.9 kW	EG
RMLR	Pequops Mt., NV	13 kW	18 kW	EG (Diesel)
RMLR	Bucks Elbow, VA	13 kW	23.5 kW	EG
RMLR	Shelby, VA	16 kW	31.4 kW	EG
RMLR	Dobson's Knob, NC	--	18 kVA	EG
RMLR	Biggerstaff Mt., NC	--	18 kVA	EG
RMLR*	Hayden, CO	--	18.75 kVA	EG
RMLR	Lay Peak, CO	--	18.75 kVA	EG
RMLR	Walton Peak, CO	--	25 kVA	EG
RMLR	Parshall, CO	--	25 kVA	EG
RMLR	Starreout, OR	--	--	EG (Gas)
RMLR	Greensprings, OR	--	--	EG (Gas)
VOR	Montebello, VA	5 kW	12 kW	EG
VOR*	Priest Mt., CA	6 kW	10 kW	EG
VOR	Pinon, NM	6.6 kW	7 kW	EG
VOR	DeLancey, NY	--	18.75 kVA	EG
VOR/DME	Schooley's Mt., NJ	4 kVA	8 kVA	EG (Diesel)
VOR/DME*	Barretts Mt., NC	--	8 kVA	EG
VORTAC	Ukiah, CA	10 W	20 kW	EG
VORTAC	Fort Jones, CA	12 kW	20 kW	EG
VORTAC	Hallock, MN	13 kW	30 kW	EG
VORTAC	Newcomerstown, OH	13.3 kW	21.8 kW	EG
VORTAC	Lake Pontchartrain, LA	14 kW	23.6 kW	EG
VORTAC	Bellaire, OH	16.3 kW	27.9 kW	EG (Gas)
VORTAC	Zanesville, OH	16.8 kW	21.5 kW	EG (Gas)
VORTAC	Newton, NJ	20 kW	40 kW	EG (Gas)
VORTAC	Stockholm Lake, NJ	20 kVA	40 kVA	EG (Gas)
VORTAC	Solberg Airport, NJ	20 kVA	40 kVA	EG (Gas)
VORTAC	Port Jervis, NY	20 kVA	40 kVA	EG (Gas)
VORTAC	Bryce Canyon, UT	20 kVA	37 kVA	EG (Diesel)
VORTAC	Anton Chico, NM	20 kW	30 kW	EG
VORTAC	Wolbach, NE	22 kW	27 kW	EG
VORTAC	Appleton, OH	22.9 kW	30.6 kW	EG (Gas)

TABLE 10. EXISTING FAA FACILITIES DIFFICULT TO ACCESS OR INACCESSIBLE DURING PERIODS OF THE YEAR (Continued)

Facility Type	Location	Estimated Power Requirement: Electronic Equipment Only	Estimated Power Requirement: Total Facility	Backup Power
VORTAC	Mankato, KS	26 kW	32 kW	EG
VORTAC	Peoria, IL	28 kVA	35.3 kVA	EG (Gas)
VORTAC	Gainesville, FL	29 kW	44 kW	EG
VORTAC	Big Sur, CA	35.6 kW	51.4 kW	EG
VORTAC	Binghamton, NY	--	37.5 kVA	EG
VORTAC	Hancock, NY	--	37.5 kVA	EG
VORTAC	Rockdale, NY	--	37.5 kVA	EG
VORTAC	Kremmling, CO	--	37.5 kVA	EG
VORTAC	Meeker, CO	--	37.5 kVA	EG
VORTAC/ RCAG	Bemidgi, MN	13 kW	32 kW	EG
RCAG	Albaquerque, NM	1.0 kW	2 kW	EG
RCAG	San Luis Obispo, CA	1.5 kW	6 kW	EG
RCAG	Priest Mt, CA	2.4 kW	8 kW	EG
RCAG	Zanesville, OH	2.6 kW	10.5 kW	EG (Gas)
RCAG	Fullerton, NE	4 kW	9 kW	EG
RCAG	Ravenna, NE	5 kW	9 kW	EG
RCAG	Buena Vista, VA	9 kW	27.6 kW	EG
RCAG	Pellston, MI	10 kW	15 kW	EG
RCAG	White Top Mt, VA	11 kW	30 kW	EG
RCAG	Bellmont, OH	12 kW	22 kW	EG
RCAG	El Yunque, PR	20 kW	30 kW	EG
RCAG	North Mt, PA	24 kW	25 kW	EG
RCAG	Bucks Elbow, VA	26 kW	55.4 kW	EG
RCAG	Barretts Mt, NC	--	18 kVA	EG
RCAG	Hayden, CO	--	25 kVA	EG
RCAG	Aspen, CO	--	25 kVA	EG
RCAG/RMLT/ RCO	Globe, AZ	24 kW	30 kW	EG
RCAG/SFO	Judith Mt, MT	400 kW	1600 kW	--
EFAS	Datil, NM	500 W	750 W	EG
RTR	Eagle, CO	--	8 kVA	EG
RCO/LCOT/ TTY	Guadalupe Pass, TX	17 kW	20 kW	EG
ARSR	Paso Robles, CA	65 kW	65 kW	EG
ARSR	Gallup, NM	75 kW	150 kW	EG

*Colocated with a RCAG facility at the same site.

between May 15 and October 1 each year. At the present time, the use of a thermoelectric generator is probably the most cost effective means, especially since the beacon is utilized only during the summer months. However, should other situations arise, such as problems associated with refueling, which could provide sufficient justification, solar photovoltaics could be offered as an alternative. In the case of the communications facility at Judith Mountain, this is an extremely remote mountain area (6,428 ft elevation) and during the winter months is accessible only by snowcat. However, the power requirement is presently beyond the capability of any currently available alternative power system.

The Alaskan Region has a number of remotely located facilities. As a result, they have had some experience using alternative power systems. At Kenai they have utilized a solar photovoltaic system to provide power to a MB (outer marker). However, it has proven to be inadequate for total use and is being modified in hopes of bringing it up to a useable level. In the Lake Clark Pass area, radiosotope thermoelectric generators have been installed that will provide continuous power (25 W - 60 W) to several self-sustained outlets. Since these were installed in late 1977, no reports on their operation have been received.

Although not meeting the criteria of being remotely located, but still being facilities with reasonably low power consumption, the following facilities, could possibly be candidates (sector field offices expressed interest) for a solar photovottaic system:

OM/LOM	Laredo, TX
MM	Laredo, TX
MTR	Omaha, NE
MTR	Lincoln, NE
MTR	Lincoln, NE
MTR	Sioux City, IA

Both MB's at Laredo, Texas presently use commercial service for primary power with batteries used as the backup source (compass locator has no backup). The field office reports that these two facilities require 1300 W and 160 W, respectively. The moving target reflectors presently use batteries for prime power and are of sufficiently low power that they would make excellent candidates for solar photovoltaics. There is a program in Washington to implement moving target reflectors at various locations (see table 7), and if photovoltaics could be applied to this program, certainly a retrofit for use at existing locations would be in order.

SUMMARY

Power consumption at FAA facilities varies from less than 100 W for moving target reflectors and marker beacons to a megawatt or more at some of the larger facilities. This is one of the essential inputs to any alternative energy life cycle cost analysis. Although these type data are usually available, they are quite dispersed, often fragmented, difficult to interpret, and are generally presented in a nonstandardized form. The FAA has no centralized collection and tabulation point where accurate energy data can be obtained. Some limited data were received from several regions and a partial examination of data from the Southwest Region was made and it indicated that the majority of the facilities require less than 10 kW.

In order to indentify potential FAA facilities where it may be feasible and cost effective to use alternative energy systems, two questionnaires were developed and distributed. One was directed toward facilities in the planning stage, while the second was aimed at existing facilities that use engine generators for prime power, have unreliable commercial power, or are remotely located and inaccessible. The results of the survey are shown in table form with a large number of facilities generally identified as being potential candidates for some type of alternative power system. One very good possibility is the moving target reflector which is still in the planning stage. It requires very low power and might be an excellent candidate for solar photovoltaics.

It should be emphasized that these initial questionnaries very broadly identified facilities, and that further in depth investigation would be required before definite decisions could be made.

CONCLUSIONS

As a result of this project investigation it is concluded that:

1. Any of the energy conversion systems that were investigated are capable of supplying electrical power. Depending upon the application, power requirements, and site location, each should be given consideration for future use at FAA facilities.

2. From the questionnaire data an excellent candidate for photovoltaics seems to be the moving target reflector, requiring very low power and often having optimum locations in areas without commercial electric power. With further analysis of this questionnaire data and some additional information, other candidates for alternative energy systems could be identified.

3. Based upon cost considerations only, none of the alternative energy systems investigated are currently cost competitive when commercial electric power is available on site. However, it is expected that the cost of commercial power will continue to rise, bringing alternative energy systems to a more cost competitive level. Of the alternative energy systems investigated, fuel cells and wind energy systems have the lowest cost per energy unit at the present time.

4. At the present time, consideration of alternative energy systems should be based upon the following general guidelines:

Low power (Less than 1000 watts continuous)

a. Photovoltaic
b. Wind
c. Thermoelectric

Medium power (1000 watts to 10,000 watts continuous)

a. Wind
b. Fuel Cells

High power (Greater than 10,000 watts continuous)

a. Fuel Cells

RECOMMENDATIONS

It is recommended that:

1. The FAA proceed to establish alternative energy demonstration sites in order to gain experience in the design, implementation, and operation of such systems. As an initial effort, the moving target reflector would be an excellent choice for photovoltaics, requiring very low power and often having optimum locations in areas without commercial electric power. Further analysis of the questionnaire data along with some additional information could result in identifying other specific facilities and sites where some form of alternative power could be utilized.

2. Due to the constantly changing and fast advancing nature of energy conversion systems, the FAA should expend some effort in continuing the literature/industry/government search initiated under this project in order to remain current on the subject. It is expected that as the development proceeds, alternative energy systems will become more cost competitive with commercial power.

3. The FAA should establish a centralized data collection and tabulation point for energy consumption data on a facility basis. In addition, an overall power study should be made on all FAA facilities to determine actual facility power requirements, plus present and projected costs of retaining existing primary and secondary backup power systems.

4. The FAA should pursue the possibility of obtaining from ERDA one of the 40 kW fuel cells currently under development with the thought of establishing a demonstration site utilizing this power source.

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APPENDIX A

AUXILIARY EQUIPMENT ASSOCIATED WITH ALTERNATIVE ENERGY SYSTEMS

POWER INVERTERS.

THEORY. Most modern inverters are solid-state devices which operate as an oscillator, the frequency of which is determined largely by the characteristics of a saturable transformer. The basic operation of a solid-state inverter can be seen with the simplified schematic diagram shown in figure A-1. T-1 is the saturable transformer, while Q1 and Q2 are matched power transistors.

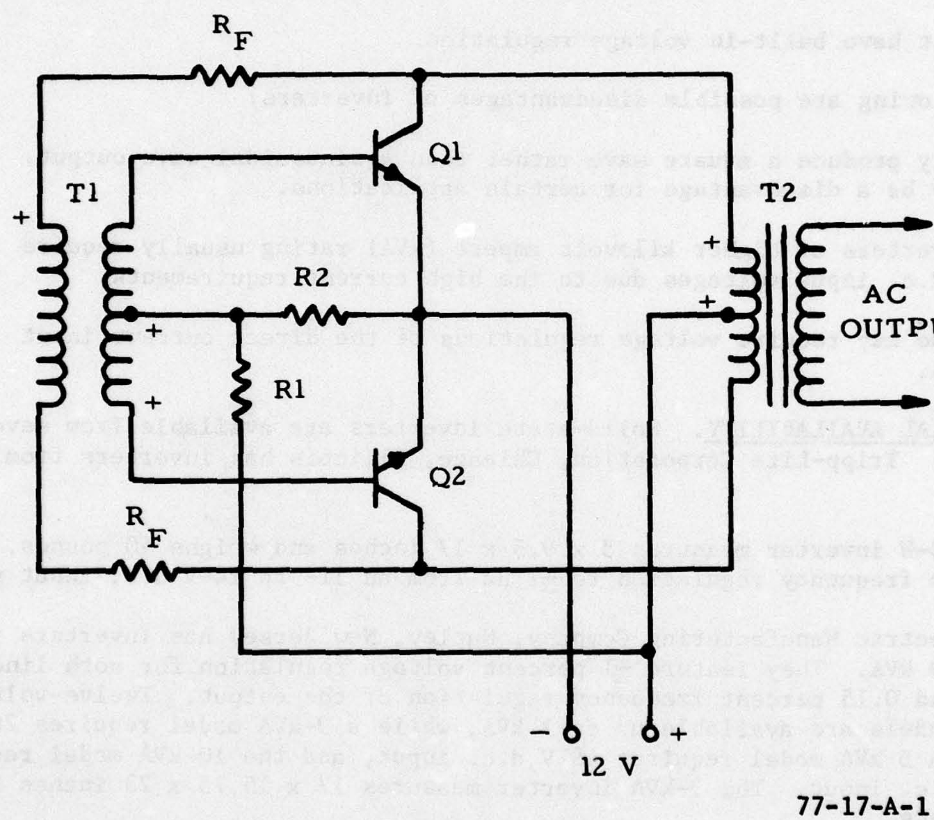

FIGURE A-1. BASIC INVERTER CIRCUIT

When the inverter is initially energized, one of the transistors of the matched pair (assume Q2) will conduct more rapidly than the other. The collector of Q2 will, therefore, be driven in a negative direction with respect to the collector of Q1 causing a difference of potential across the primary of saturation transformer T1, as shown by the + sign. This results in a positive feedback which drives the base of Q2 positive with respect to that of Q1. This further forward-biases Q2 and reverse-biases Q1, so that Q1 is cut off and Q2 is driven into saturation.

A new half-cycle of operation begins as the voltage across the feedback resistors (R_F) increase slowly with the increasing magnetic current in the saturable transformer. At saturation, the voltage across the lower half of the secondary of T1 decreases, thereby taking Q2 out of saturation and Q1 out of cut-off. A 120 V., 60-Hz square wave is developed across the secondary of output transformer T2. By use of appropriate circuitry, stepped or full sinusoidal outputs can also be provided.

ADVANTAGES AND DISADVANTAGES. Advantages of inverters are outlined as follows:

1. Good reliability.

2. Available in sizes up to 10 kW.

3. Most have built-in voltage regulation.

The following are possible disadvantages of inverters:

1. Many produce a square wave rather than a sinusoidal wave output. This may be a disadvantage for certain applications.

2. Inverters of higher kilovolt ampere (kVA) rating usually require higher d.c. input voltages due to the high current requirements.

3. Some may require voltage regulations of the direct current input voltages.

COMMERCIAL AVAILABILITY. Solid-state inverters are available from several sources. Tripp-Lite Corporation, Chicago, Illinois has inverters from 60 to 1000 W.

The 1000-W inverter measures 5 x 9.5 x 17 inches and weighs 40 pounds. It features frequency regulation to $\pm$1 Hz from an 11- to 14-V d.c. input source.

Nova Electric Manufacturing Company, Nutley, New Jersey has inverters ranging up to 10 kVA. They feature $\pm$1 percent voltage regulation for both line and load, and 0.15 percent frequency regulation of the output. Twelve-volt d.c. input models are available up to 1 kVA, while a 3-kVA model requires 28 V d.c. input, a 5 kVA model requires 48 V d.c. input, and the 10-kVA model requires 120 V d.c. input. The 3-kVA inverter measures 17 x 15.75 x 23 inches and weighs 240 pounds.

Wilmore Electronics, Durham, North Carolina offers inverters of up to 500 W featuring both square wave and sinusoidal outputs. They are specially adaptable to standby and portable power systems, and can be paralleled to provide 1000 W. Voltage regulation proportional to the d.c. input is provided.

Other sources of inverters are: Advance Conversion Devices Company, Passaic, New Jersey; Terado Corporation, St. Paul, Minnesota; and Topaz Electronics, San Diego, California.

AUXILIARY EQUIPMENT REQUIREMENTS. Voltage regulator circuits may be required to keep supply voltage constant to insure a more constant operating frequency. Filtering may be required for the alternating current output.

MAINTENANCE CONSIDERATIONS. Since solid-state inverters use no moving parts, preventive maintenance should be minimal. Many inverters incorporate built-in voltage regulators, and these may require periodic adjustment. At least one contractor (Advance Conversion Devices Company) has the transistors and integrated circuits of their inverters mounted on plug-in sockets, thereby facilitating replacement of components.

COST DATA. Typical inverter prices are \$3200 for a 22 to 32 V d.c. input 3-kW inverter from Nova Manufacturing Company. A 2-kW inverter from the same company costs \$2460. A typical GSA price for a 1 kVA, 24 V d.c. inverter by Advance Conversion Devices Company is \$1135. A typical price for a smaller inverter is \$295 for a 300 W frequency-stable inverter from Wilmore Electronics. A 60-W inverter is available from Tripp-Lite for less than \$30.

SPECIFICATION CRITERIA. Criteria to be considered in preparing specifications for inverters are listed below.

1. Input voltage.

2. Output voltage, power, frequency, and power factor.

3. Requirements for built-in or external voltage regulation.

4. Output filtering.

5. Output waveform.

6. Maximum physical dimensions and weight.

7. Contractually specified and minimum-acceptable "mean-time-between-failure" (MTBF) and "mean-downtime."

8. Preventive maintenance.

D.C.-TO-D.C. CONVERTERS.

THEORY. Direct current-to-direct current converters may be rotary types, vibrator or chopper types, or solid-state. The a.c. voltage produced by the vibrator, chopper, or saturable transformer is then rectified back to d.c., generally by a bridge rectifier.

APPLICATION. Direct current-to-direct current converters are generally used for driving integrated circuits, digital applications, and other small power applications generally less than 100 W. However, larger d.c. to d.c. converters providing 600 W are available for industrial use. Output voltages can vary from as low as 5 V up to 2500 V or greater. They provide isolation

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of the d.c. load from the battery source with voltage regulation of line and load to within a fraction of 1 percent. Costs generally range from \$6 to about \$500. Calculated MTBF for typical units range from 20,000 to 55,000 hours.

COMMERCIAL AVAILABILITY. Direct current-to-direct current converters of low power capability (less than 100 W) are available from several sources: Abbott Company, Los Angeles, California; Stevens-Arnold, South Boston, Massachusetts; and Semiconductor Circuits, Haverhill, Massachusetts. Wilmore Electronics, Durham, North Carolina provides larger type converters for industrial use. They are available in sizes up to 600 W.

SPECIFICATION CRITERIA. Criteria to be considered in preparing specifications for d.c.-to-d.c. converters are listed as follows:

1. Input and output voltage, current and power.

2. Line and load voltage regulation.

3. Physical dimensions and weight.

4. Contractually required minimum acceptable MTBF and mean downtime.

5. Preventive maintenance.

6. Type of converter-chopper, solid-state, or vibrator.

VOLTAGE REGULATORS.

THEORY. One of the simplest voltage regulators is a Zener diode. This device has the characteristic of maintaining a nearly uniform voltage drop across it over a wide current range. More precise voltage regulation is achieved by comparing all or part of the output voltage against some reference voltage. Zener diodes are often used to supply this constant reference voltage. Any change in output voltage caused either by variation of input (line) voltage or variation of load current due to fluctuations in the load will be manifested by an error voltage from the comparing circuit. This error voltage is applied to a regulating element which electronically counteracts the variation in the output voltage.

Two common types of voltage regulators are the series and shunt types, depending upon the position of the regulating element with respect to the load. Each of these will be described below.

SERIES VOLTAGE REGULATOR. Figure A-2 illustrates a very simple type series voltage regulator. Q1 is the comparison circuit in which a portion of the output voltage is compared against the 12 V reference voltage drop across the Zener diode. The difference, or error signal, is amplified by Q2, then applied to the regulating element, Q3, which is in series with the load.

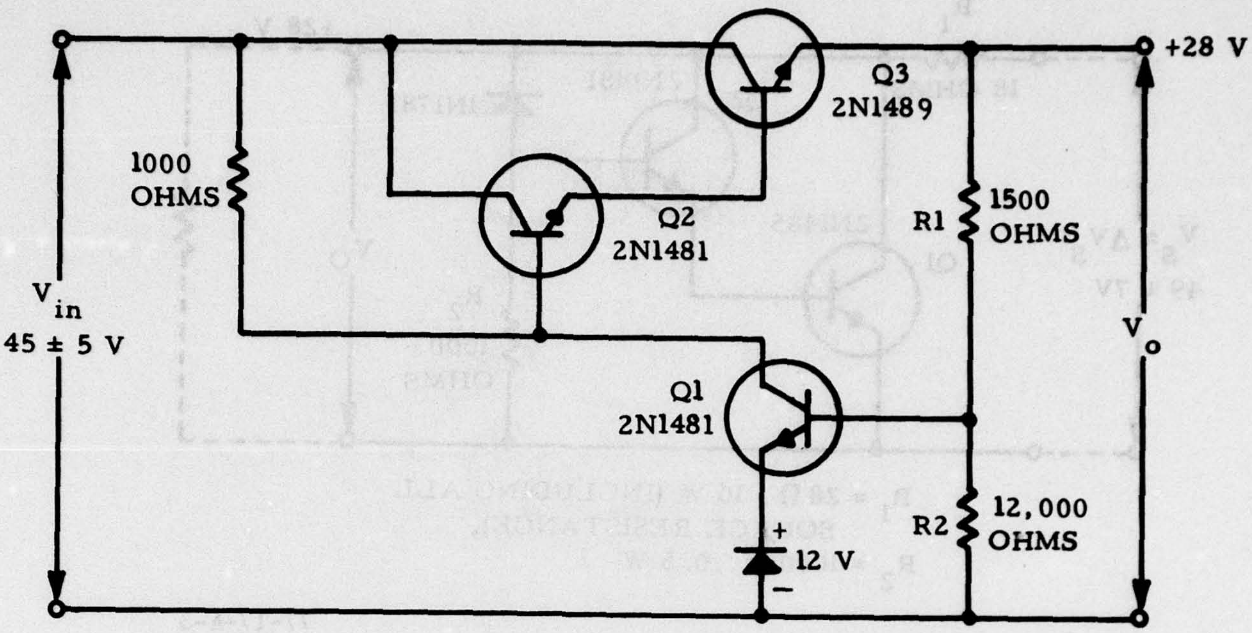

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FIGURE A-2. SERIES VOLTAGE REGULATOR

To see how this circuit works, assume that due to either a rise in input voltage, or a change in load characteristics, the output voltage across the load, V_O, tended to rise. This will increase the voltage drop across R2 due to the voltage-divider action of resistors R1 and R2. This increases the forward bias of the emitter-base junction of Q1, therefore, lowering the collector-to-emitter voltage drop across Q1. This causes the base of Q2 to become less positive which drives the base of series regulating transistor Q3 in a less positive direction due to the emitter-follower action of Q2. The emitter-base junction of Q3, consequently, becomes less forward-biased, increasing its collector-to-emitter voltage drop; therefore, the incremental voltage rise across the load is largely absorbed by Q3, which tends to keep the output voltage constant.

SHUNT VOLTAGE REGULATOR. Figure A-3 illustrates a very simple type shunt voltage regulator. Shunt regulators of this type are less complex than series-type voltage regulators, although they are not quite as efficient.

A shunt regulator uses a voltage reference element and a shunt element. In this circuit, the output voltage remains constant because the shunt element current changes when either the input voltage or the load current changes. The change in the shunt current appears as a change in voltage across the resistor R1, that is in series with the load.

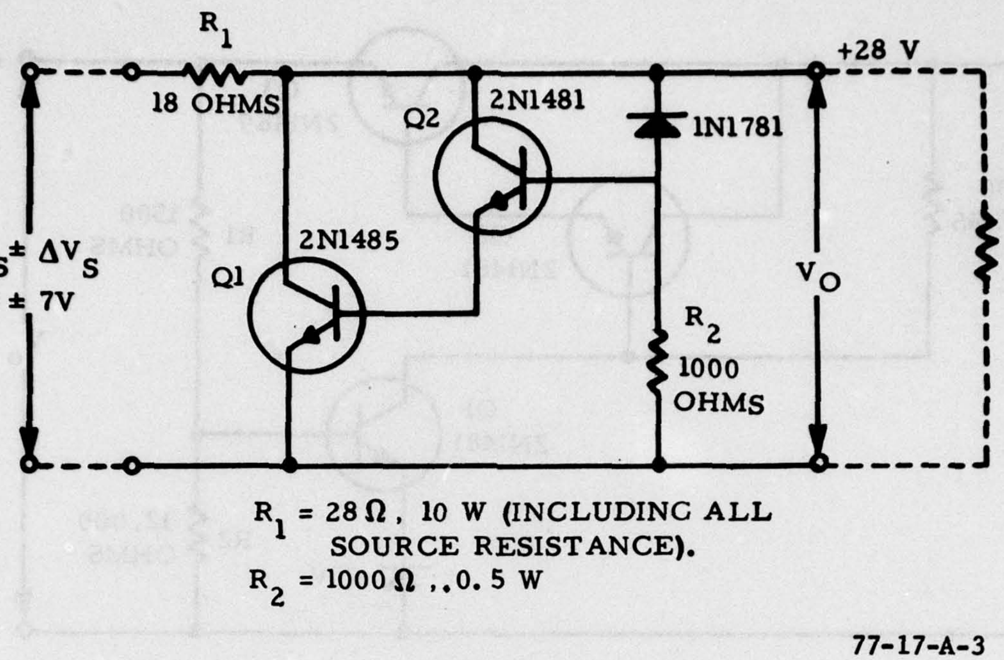

FIGURE A-3. SHUNT VOLTAGE REGULATOR

The reference element is Zener diode 1N1781, which has a nominal 27-V drop. Thus, any change in output voltage will be reflected by a corresponding change in voltage drop across R2. Assume the output voltage, V_O, tends to decrease. This will decrease the emitter-base junction forward bias on Q2, which, by emitter-follower action, causes a decrease in emitter-base forward bias of shunt element Q1. This decreases the collector-to-emitter current of Q1, thereby decreasing the voltage drop across series resistor R1. Since the incremental decrease in output voltage is absorbed by series resistor R1, the output voltage tends to remain constant.

__APPLICATION__. Voltage regulation circuitry is often designed into inverters, d.c.-to-d.c. converters, and other power conditioning devices. In many cases, the output of the battery supply may require voltage regulation before application to the power-conditioning equipment, particularly if the internal resistance of the batteries is relatively high. Direct current voltage regulators for this purpose are available from Beckman Instruments of Fullerton, California. They are applicable for input voltages up to 45 V and load currents up to 0.75 ampere. Depending on degree of regulation and other factors, prices range from about $10 to $55.

__ADVANTAGES AND DISADVANTAGES__. Voltage regulators have the advantage of maintaining output voltages within specified tolerances when larger variations of input voltage or output load current are experienced. Part of the price paid for this is that some of the input voltage is consumed across the regulating element or series resistor. Voltage regulation circuitry is often

designed into the inverters or d.c.-to-d.c. converters, but this increases the circuit complexity, lowering the reliability. Many voltage regulators have adjustable outputs whereby the desired output voltage can be selected.

SPECIFICATION CRITERIA. Criteria to be considered in preparing specifications for voltage regulators or voltage-regulating circuitry are listed as follows:

1. Separate voltage regulator, or integrated into inverter/converter.

2. Series, shunt, or other type circuitry.

3. Line and load voltage regulation.

4. Input, output voltage and current.

5. Physical dimensions and weight (for separate regulators).

6. Contractually-required and minimum-acceptable mean-time-to-failure and mean-downtime.

APPENDIX B

CRITERIA TO BE CONSIDERED WITH ALTERNATIVE POWER SYSTEMS

GENERAL.

SITE INFORMATION.

1. Name of facility requiring power.

2. Function of facility requiring power.

3. Priority of facility requiring power.

SITE DESCRIPTION.

1. Description of physical environment.

2. Description of general weather conditions.

3. Analyze coast and geodetic maps and National Oceanic and Atmospheric Administration (NOAA) climatological data. Record peak and average winds, snow, rain, temperatures, and describe any turbulence. Collect insolation and wind data from the actual site, if possible.

POWER REQUIREMENTS.

1. Describe the load; critical/non-critical, continuous/intermittent, a.c./d.c. voltage, current, and power (peak and/or average).

2. Source and type of existing power.

3. Backup power; available/unavailable, type, size, and fuel.

4. Heating and cooling; type and size.

LOGISTICS.

1. Commercial power, available/unavailable. If available, quantity utilized and cost. If unavailable, source of power and cost to implement commercial power.

2. Maintenance requirements; manned/unmanned site.

3. Site accessibility.

4. Human needs; heating/cooling/water.

5. Fuel availability; type, quantity, storage, and cost per unit.

SPECIAL CONSIDERATIONS.

1. Physical obstructions; description, location.

2. Interference; power source cannot interfer with operational characteristics of facility.

3. Human considerations.

ALTERNATIVE POWER SYSTEMS CONSIDERATIONS.

SOLAR PHOTOVOLTAIC SYSTEM.

1. Considered practical for low-power applications (less than 1000 W continuous).

2. Site location must have an unshaded southern exposure.

3. Cells are generally rated in peak watts. For a continuous power requirement, a factor of 3 to 10 times must be applied to the continuous power output, dependent upon isolation available at the location.

4. In most applications, a storage medium must be provided. At the present time, the only practical and cost effective method is the storage battery.

5. Generally cells operate more efficiently in cool climates. For each Centigrade degree increase in operating temperature above ambient (25° C), the efficiency of the cell decreases approximately 1/4 percent.

WIND ENERGY SYSTEMS.

1. Considered practical for low and medium power applications (less than 10,000 W continuous).

2. In wind systems, output is usually stated in terms of rated power. For a continuous power requirement, a factor of 5 to 10 times the continuous power should be applied, dependent upon available winds at the location.

3. General rule of thumb is that wind speeds near the earth's surface increase as the 1/7 power of the height above the earth. To determine tower height a cost analysis of increased tower height versus increased windspeed must be made.

4. In most applications a storage medium must be provided. Currently the most cost effective means is the storage battery.

5. Wind shear and consequently the available wind power is affected by the roughness of the earth's surface in a given location. This means buildings, trees, etc., at a given site can create wind shear problems.

6. Streamlines of a windstream are compressed and its flow is accelerated as it passes over a hill or through a narrow valley. Average power output may be increased by proper siting to take advantage of these anomalies.

7. The features of a suitable site are as follows:

a. High annual average windspeed.

b. No tall obstructions upwind for a distance depending on the height of the tower.

c. Top of a smooth well-rounded hill on flat plain or island in a lake or sea.

d. Open plain or open shoreline.

e. Mountain gap that produces a funneling effect.

FUEL CELL SYSTEMS.

1. Considered practical for medium and high power applications (greater than 10,000 W continuous).

2. With present technology, efficiencies of fuel cells range from 37 to 40 percent. Planned technological advancements forecast efficiencies in the 50- to 60-percent range.

3. Fuel cell efficiency remains nearly constant from partial to full load conditions.

4. Fuel cells must be sized to meet the peak load requirements.

5. Heat is a by-product of the fuel cell. Recovery of this heat for heating and cooling through the use of a heat pump or similar device would further increase the overall efficiency of the fuel cell.

6. Fuel must be supplied to the fuel cell. Some fuel types are: methanol, ammonia, hydrogen, propane, and natural gas. Therefore, fuel availability, storage, and cost must be considered.

THERMOELECTRIC AND THERMIONIC GENERATORS.

FOSSIL FUELED THERMOELECTRIC GENERATORS.

1. Units up to 90 W are commercially available using propane, butane, and natural gas as the fuel for the flameless heat source.

2. Useful in remote locations where maintenance and frequent refueling trips are not possible and/or where size and weight is a problem (weighs less than 200 pounds).

3. Considered relatively inexpensive, easy to operate, easy to maintain, and provides a constant power output over a wide range of climatic conditions.

4. Availability, cost and storage of fuel must be given consideration.

RADIOISOTOPE FUELED THERMOELECTRIC GENERATORS.

1. Units up to approximately 100 W are available.

2. Weight is a restriction. A 100-W unit weighs more than 4000 pounds.

3. Particularly useful for remote or inaccessible locations where constant, continuous, electrical power is required for long periods (years) without refueling or maintenance.

4. By amortizing the initial cost of a thermoelectric generator with a radioisotope heat source over a period of its life, the cost per kilowatt-hour is still significantly higher than the use of fossil fuels.

THERMIONIC GENERATORS.

1. The present state of technology is such that the use of thermionic generators is not yet economically feasible. This is a long term possibility only.

APPENDIX C

EASTERN AND NEW ENGLAND REGION POWER CONSUMPTION DATA

EASTERN REGION POWER CONSUMPTION DATA

Constant for Averaging
8,760 h/yr

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
ALS	UCA	80,605	3,642	9.2
	SYR	147,600	7,979	16.9
	FND	63,800	3,339	7.3
	BAL	128,600	6,413	14.7
	GBI	48,240	4,066	5.5
	BUF	181,650	7,969	20.8
	IAG	112,662	4,304	12.9
	MCH	108,900	8,535	12.4
	ROC	89,400	5,743	10.2
	CRW	170,981	8,214	19.5
	UHW	76,760	3,273	8.8
	ELM	89,280	4,909	10.2
	ORF	37,400	2,385	4.3
	PHF	43,000	2,511	4.9
	ORF	12,660	780	1 4
	RIC	40,200	2,391	4.6
	RIC	51,700	2,535	5.9
	RIC	32,100	1,740	3.7
	PHF	1,285	103	0.1
	HLG	36,200	1,581	4.1
	ROA	86,520	3,896	9.9
	LYH	173,640	6,682	19.8
	HPN	77,760	7,425	8.9
ARSR	UCA	496,560	14,964	56.7
	UCA	18,147	818	2.1
	DCA	512,230	13,647	58.5
	BED	454,800	14,622	52.0
	BNTN	544,500	9,692	62.2

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
ARTCC	ISP	76,338	3,876	8.7
	NY	12,128,341	463,192	1386.1
	ZDC	15,220	852	1.7
	ZDC	9,780,522	219,884	1117.8
ASR	BAL	54,062	2,773	6.2
	BAL	224,200	9,048	25.6
	LSTN	15,680	518	1.8
	HTS	205,538	6,703	23.5
	ERI	126,646	2,967	14.5
	ELM	229,122	6,852	26.2
	ACY	126,289	2,408	14.4
	RIC	253,800	9,153	29.0
	BGM	153,600	5,249	17.6
	HPN	223,500	14,825	25.5
	BUF	285,120	8,271	32.6
	CRW	143,840	4,734	16.4
ATCT	ALB	556,505	13,039	63.6
	HGR	130,740	2,726	14.9
	HTS	192,485	6,179	22.0
	CKB	134,280	3,472	15.3
	PKB	118,360	4,121	13.5
	MGW	133,600	4,670	15.3
	ERI	225,240	5,546	25.7
	ERI	920	45	0.1
	ERI	120,960	5,015	13.8
	ITH	159,600	5,106	18.2
	ELM	166,140	5,801	19.0
	LGA	568,200	47,781	64.7
	LGA	133,200	17,002	15.2
	WSY	646,200	31,298	73.9
	ISP	46,710	2,368	5.3
	DWL	42,810	2,500	4.9
	TEB	158,250	7,666	18.1
	PHF	137,940	5,624	15.8
	SBY	185,680	7,153	21.2
	PHF	126,500	5,163	14.5
	FSS	256,530	8,564	29.3
	PNE	154,112	9,181	17.6
	ILG	29,617	1,210	3.4
	ILG	46,985	1,034	5.4
	PHL	129,160	3,668	14.8
	HLG	65,080	3,863	7.4
	LYH	61,592	1,692	7.0
	POU	130,374	6,734	14.9

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
FSS	RQY	53,594	2,132	6.1
	ALB	62,856	2,144	7.2
	ALB	49,440	2,174	5.7
	MRB	105,320	3,856	12.0
	BUF	507,774	15,972	58.0
	MGW	118,640	3,949	13.6
	BLF	108,440	3,748	12.4
	DUJ	72,240	3,529	8.3
	JST	27,136	1,263	3.1
	BFD	85,223	2,812	9.7
	ERI	59,400	4,035	6.8
	ISP	53,088	2,710	6.1
	ISP	232,800	10,774	29.6
	ORO	4,440	377	0.5
	MIV	137,513	6,444	15.7
	RIC	128,200	5,797	14.7
	PIT	6,724	277	0.8
	DAN	48,612	1,631	5.6
	DAN	76,966	2,685	8.8
	CHO	74,070	3,356	8.5
	POU	112,308	5,642	12.8
	EKN	5,013	372	0.6
	MIV	80,980	3,576	9.3
FM	GFL	3,462	219	0.4
	HTS	8,197	320	0.9
	PKB	5,559	320	0.6
GS	ALB	23,414	770	2.7
	GFL	21,280	987	2.4
	SYR	25,916	779	3.0
	FND	6,726	419	0.8
	HGR	7,798	259	0.9
	GBI	1,616,400	7,069	184.7
	BUF	12,851	471	1.5
	MWD	20,800	831	2.4
	HTS	14,866	596	1.7
	MGW	11,140	762	1.3
	CKB	7,196	418	0.8
	BLF	14,410	554	1.6
	DUJ	14,270	807	1.6
	FKL	9,840	463	1.1
	ACO	15,560	707	1.8
	BFD	47,480	2,091	5.4

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
GS	JHW	13,570	717	1.6
	PSB	13,440	651	1.5
	ELM	93,120	3,416	10.6
	ITH	13,123	536	1.5
	MMU	12,580	885	1.4
	ORF	4,360	325	0.5
	SBY	6,296	470	0.7
	RIC	10,990	713	1.3
	RIC	13,560	846	1.5
	ABE	9,668	305	1.1
	PSK	7,149	290	0.8
	HSP	16,910	765	1.9
	CHO	9,550	635	1.1
	SHD	9,040	510	1.0
	POU	9,415	595	1.1
H	RME	7,000	363	0.8
	AVN	9,207	499	1.1
	BBO	12,836	445	1.5
	RQY	12,466	768	1.4
	BFD	5,648	267	0.6
	ERI	2,440	176	0.3
	ELM	8,279	362	0.9
	BBN	4,197	257	0.5
	CAT	5,827	451	0.7
	LYH	46,418	2,223	5.3
	BTP	6,056	295	0.7
	VIT	8,235	397	0.9
	ROA	36,552	1,040	4.2
	EVI	4,552	320	0.5
	CHO	7,240	527	0.8
	GTN	150	37	0.0
	BGM	4,818	240	0.6
ILS	SCHN	2,523	159	0.3
	ALB	11,332	488	1.3
	ALB	4,996	229	0.6
	SYR	2,964	145	0.3
	CRW	153,600	4,852	17.6
	DUJ	36,570	1,969	4.2
	JST	38,260	1,159	4.4
	JFK	4,380	280	0.5

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
ILS/LOC	ZNY	3,164	224	0 4
ILS/MAL	ZNY	3,671	218	0.4
ILS/MM	ZNY	400	26	0.0
ILS	ORF	7,520	488	0.9
	ORF	24,070	1,395	2.8
ILS/MM	NORF	288	8	0.0
ILS	ILG	34,872	1,860	4.0
ILS/OM	PHL	6,346	304	0.7
ILS/GS	RNKE	3,403	120	0.4
ILS/MAP	RNKE	182	12	0.0
ILS/OM	RNKE	88	5.5	0.0
ILS/ASR	ROA	170,026	5,026	19.4
ILS/OM	CHNTILY	264	25	0.0
	IAD	11,860	823	1.9
ILS/MM	BGM	384	38	0.0
ILS/OM	BGM	840	170	0.1
LOC	ALB	38,620	2,246	4.4
	GFL	13,157	653	1.5
	UCA	5,991	165	0.7
	ART	5,292	309	0.6
	FND	54,245	2,908	6.2
	MRB	20,560	845	2.3
	BAL	26,998	1,573	3.1
	HGR	10,839	426	1.2
	BUF	1,818,156	1,821	207.8
	IAG	115,632	4,670	0.5
	HTS	57,270	1,942	0.2
	PKB	21,591	1,299	2.5
	BKW	24,808	815	2.8
	MGW	30,105	1,331	3.4
	CKB	24,923	1,603	2.8
	PSK	33,778	1,180	3.9

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
LOC	BLF	35,271	1,225	4.0
	FKL	9,240	470	1.1
	AOO	15,602	1,027	1.8
	BFD	28,440	1,063	3.3
	ERI	78,110	2,338	8.9
	JHW	14,910	768	1.7
	PSB	38,340	1,161	4.4
	RVL	34,880	1,210	4.0
	MMU	27,040	1,636	3.1
	EWR	21,908	1,359	2.5
	ACY	1,906	185	0.2
	PHF	71,280	3,257	8.1
	SBY	6,296	470	0.7
	ABE	10,688	414	1.2
	HSP	25,330	920	2.9
	LYH	110,640	3,160	12.6
	CHO	37,790	1,983	4.3
	SHD	25,990	1,202	3.0
	AVP	84,752	2,582	9.7
	HZL	9,600	422	1.1
	POU	9,839	621	1.1
MALSR	HNTY	6,052	344	0.7
	SYR	4,765	229	1.5
	PKB	7,343	428	0.8
	LWB	3,900	289	0.4
	CKB	10,792	590	1.2
	MGW	7,392	543	0.8
	DUJ	9,720	564	1.1
	ADU	4,200	230	0.5
	FKL	7,300	481	0.8
	PSB	18,664	895	2.1
	ITH	12,560	592	1.4
	ISP	7,746	484	0.9
	MMU	8,731	681	1.0
	SBY	1,835	173	0.2
	LLTN	1,442	87	0.2
	PSK	3,867	176	0.4
	CHO	7,340	516	0.8
	SHD	3,800	250	0.4
	HZL	1,567	137	0.2
	POU	10,613	648	1.2
	JST	15,480	786	1.8

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
MM	ALB	12,666	622	1.4
	ALB	44,550	2,750	5.1
	ALB	16,140	806	1.8
	PHF	215,661	4,341	24.6
	SYR	35,594	1,192	4.1
	SYR	9,339	390	1.1
	BAL	1,430	103	0.2
	HGR	4,385	150	0.5
	MXK	5,480	324	0.6
	GBI	4,705	238	0.5
	BUF	26,208	1,105	3.0
	IAG	10,467	562	1.2
	ROC	4,830	126	0.6
	MWD	5,040	345	0.6
	CRW	5,394	237	0.6
	HTS	4,984	203	0.6
	LWB	7,830	516	0.9
	BKW	4,573	187	0.5
	EKN	12,496	664	1.4
	DUJ	5,900	360	0.6
	FKL	3,610	225	0.4
	JST	244	27	0.0
	AOO	4,210	242	0.5
	BFD	3,810	216	0.4
	JHW	1,160	94	0.1
	ERI	21,340	837	2.4
	ERI	200	26	0.0
	ELM	6,816	310	0.8
	ITH	3,423	180	0.4
	JFK	4,050	436	0.5
	LGA	2,541	277	0.3
	RVH	4,668	307	0.5
	ISP	3,771	230	0.4
	FRG	526	54	0.0
	EWR	5,480	285	0.6
	ORF	4,410	353	0.5
	SBY	323	41	0.0
	RIC	1,290	112	0.1
	RIC	8,820	569	1.0
	ILG	1,032	19	0.1
	ABE	2,112	123	0.2
	PIT	3,447	283	0.4
	PIT	2,004	168	0.2
	HLG	1,570	88	0.2
	PSK	636	40	0.6
	ROA	7,522	284	0.9
	LYH	4,520	188	0.5

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
MM	CHO	480	47	0.0
	SHD	46	11.5	0.0
	BGM	22,848	883	2.6
OM	SYR	11,297	636	1.3
	UCA	2,019	150	0.2
	SYR	35,594	1,192	4.1
	FND	6,324	393	0.7
	MRB	5,605	290	0.6
	BAL	29,009	787	3.3
	RWS	5,981	202	0.7
	FNB	8,300	514	0.9
	HGR	9,337	330	1.1
	GBI	10,520	517	1.2
	IAG	9,162	503	1.0
	ROC	3,643	243	0.4
	MWD	4,421	279	0.5
	MCU	8,396	434	1.0
	CRW	5,276	234	0.6
	HTS	129,965	3,560	14.9
	PKB	4,605	286	0.5
	MGW	594	44.5	0.0
	CKB	5,132	314	0.6
	EKN	3,397	232	0.4
	PSK	288	30	0.0
	BLF	2,169	116	0.2
	DUJ	7,970	480	0.9
	JST	810	57	0.1
	FKL	3,610	225	0.4
	AOO	3,990	224	0.5
	ERI	9,600	545	1.1
	PSB	2,211	103	0.3
	RVL	2,060	142	0.2
	ELM	5,628	263	0.6
	ITH	6,337	302	0.7
	IWY	9,125	539	1.0
	JFK	4,200	265	0.5
	JFK	1,800	206	0.2
	JFK	23,511	1,338	2.7
	JFK	9,785	578	1.1
	LGA	8,030	810	0.9
	LGA	8,501	892	1.0
	RVH	7,624	420	0.9
	FRG	1,054	86	0.1
	ISP	8,404	493	1.0
	CTO	5,256	199	0.6

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
OM	EWR	1,698	169	0.2
	PHF	4,410	353	0.5
	SBY	9,120	406	1.0
	RIC	7,930	542	0.9
	RIC	650	57	0.1
	RIC	3,950	289	0.5
	ILG	4,728	415	0.5
	ABE	1,600	85	0.2
	HLG	7,647	239	0.9
	HSP	6,550	325	0.7
	ROA	3,521	173	0.4
	LYH	5,223	212	0.6
	SHD	7,390	425	0.8
	DLX	400	56	0.0
	DLX	2,700	229	0.3
	HZL	626	51	0.1
	BGM	74,364	2,783	0.3
	HPN	77,760	7,425	8.9
	POU	3,000	223	0.3
RCAG	CIT	69,636	2,924	7.9
	CRW	69,040	2,439	7.9
	PMH	43,393	1,224	5.0
	PMH	49,090	2,470	5.6
	PKB	38,799	1,410	4.4
	QDR	62,390	1,624	7.1
	FTZA	32,390	1,522	3.7
	FTZA	77,560	3,107	8.9
	QJT	38,136	1,515	4.4
	JFK	68,610	5,086	7.8
	QWW	63,177	2,407	7.2
	QRB	113,440	4,857	12.9
RMLR	QWR	47,760	1,681	5.5
	QWI	63,857	1,671	7.3
	QWK	48,620	1,893	5.6
	QWJ	44,436	1,841	5.1
	QWL	46,392	1,959	5.3
	CTO	59,460	2,517	1.8
	QWU	63,342	4,149	7.2
	QRF	43,680	2,333	5.0
	QRG	42,259	2,347	4.8
	QWT	52,530	2,737	6.0
	QWQ	41,650	2,187	4.8
	QRW	26,490	1,432	3.0
	RIC	25,980	1,374	3.0
	QRY	32,920	1,757	3.8

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
RMLR	QRZ	28,420	1,537	3.2
	QWW	37,410	1,562	4.3
	QRB	53,400	2,633	6.1
	QWY	24,667	871	2.8
	DCA	28,786	1,401	3.3
	QRV	28,700	1,307	3.3
	QRV	32,030	1,735	3.7
	DCA	36,930	1,972	4.2
	ROC	155,280	7,848	17.7
RAIL	PSK	1,249	72	0.1
RTR	UCA	35,417	1,552	4.0
	SYR	51,036	3,010	5.8
	BUF	40,248	1,522	4.6
	ROC	4,290	164	0.5
	CRW	40,590	1,351	4.6
	HTS	32,276	1,227	3.7
	MMU	30,971	1,683	3.5
	PHL	46,480	1,319	5.3
	HLG	27,730	1,102	3.2
	ROA	45,240	1,811	5.2
	LYH	21,746	709	2.5
	DCA	42,410	2,221	4.8
	BGM	35,364	1,342	4.0
RVR	SYR	6,928	421	0.8
	BUF	8,472	381	1.0
REIL	BUF	365	41	0.0
	CKB	3,986	259	0.5
	TTN	924	123	0.1
	ROA	575	35	0.1
VASI	MRB	16,049	737	1.8
	BAL	14,828	900	1.7
	BKW	13,938	473	1.6
	CKB	11,917	636	1.4
	RIC	24,800	1,430	2.8
	RIC	13,760	866	1.6
	ILG	11,002	628	1.3
	BING	1,956	82	0.7

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
VOR	ALB	171,360	6,486	19.6
	ALB	111,921	4,280	12.8
	ALB	62,928	2,260	7.2
	PLB	209,280	7,356	23.9
	CAM	124,083	5,133	14.2
	SYR	182,880	7,145	20.9
	UCA	180,060	5,955	20.6
	GGT	124,594	5,138	14.2
	MRB	171,810	6,251	19.6
	BAL	221,714	8,549	25.3
	EMI	140,241	5,972	16.0
	LDN	162,900	3,833	18.6
	KSL	95,520	3,535	10.9
	FDK	54,880	1,637	6.3
	HGR	32,220	888	3.7
	OTT	153,880	3,793	17.6
	DKK	146,634	5,281	16.7
	BUF	123,400	6,605	20.7
	ROC	466,110	15,310	53.2
	BKW	110,297	3,784	12.6
	RNL	41,400	1,363	4.7
	CKB	39,200	1,497	4.5
	BLF	134,240	3,933	15.3
	PSK	195,280	5,383	22.3
	SLT	124,800	4,553	14.2
	JST	234,720	5,330	26.8
	FTZA	109,120	4,904	12.5
	BFD	148,920	3,747	17.0
	JFK	50,688	3,620	5.8
	TEB	42,624	2,443	4.9
	ROA	191,760	5,630	21.9
	MOL	36,437	1,483	4.2
	LYH	155,300	4,452	17.7
	SBU	184,240	7,650	21.0
	DAN	54,618	1,918	6.2
	GVE	198,840	7,133	22.7
VORTAC	GFL	164,240	6,344	18.7
	CSN	62,530	2,869	7.1
	CRW	204,400	6,713	23.2
	HNN	174,360	5,778	19.9
	YRK	107,828	2,966	12.3
	ECB	7,379	368	0.8
	PKB	159,450	5,786	18.2
	EKN	196,640	5,820	22.8
	MGW	131,400	4,580	15.0

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
VORTAC	CKB	39,200	1,497	4.5
	GRT	137,400	3,525	15.7
	BLF	113,340	3,910	12.9
	ERI	139,280	3,210	15.9
	ETC	117,400	2,777	13.4
	PSB	67,916	1,762	7.8
	TON	148,500	3,730	17.0
	SFK	146,760	3,415	16.8
	ELM	77,040	2,771	8.8
	IPT	85,200	2,749	9.7
	RVH	176,310	10,005	20.1
	PTC	191,700	8,881	21.9
	DPK	99,900	5,683	11.4
	SBJ	203,920	8,400	23.3
	TEB	217,800	8,764	24.9
	RBV	157,100	6,517	17.9
	CYN	203,840	8,293	23.3
	ACY	186,960	7,343	21.3
	MIV	175,520	6,911	20.0
	BRV	141,050	6,081	16.1
	FKN	138,900	4,993	15.9
	SBY	75,720	4,256	8.6
	ATR	23,428	887	2.7
	RIC	186,540	7,857	21.3
	CCV	141,600	6,051	16.2
	RIC	188,520	7,899	21.5
	LVL	116,760	5,096	13.3
	ILG	171,248	7,029	19.5
	EWT	146,340	7,504	16.7
	EWC	171,200	4,643	19.5
	PIT	161,064	4,691	18.4
	IHD	119,000	4,591	13.6
	HLG	169,200	4,930	19.3
	IAD	68,430	2,658	7.8
	HUD	78,900	4,542	9.0
	AVP	172,363	4,700	19.7
	BGM	161,520	5,559	18.4
	RKA	143,280	4,791	16.4
	HNK	130,930	5,249	14.9
	CMK	158,000	5,152	18.0
	POU	148,680	7,441	17.0

NEW ENGLAND POWER CONSUMPTION DATA

Constant for Averaging
8,760 h/yr

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
ALS	PWN	192,500	7,775	21.97
	BTV	86,600	3,137	9.89
	ACK	108,957	10,332	12.44
	PVD	20,700	1,269	2.39
	EWB	206,960	11,941	23.63
	HYA	119,000	5,846	13.58
	BDL	13,400	1,295	1.53
ARTCC	ZWB	82,440	3,387	9.41
ASR	PWM	134,880	4,149	15.40
	BTV	291,528	8,749	33.28
ATCT	PWM	577,200	14,972	65.89
	BOS	77,700	4,840	8.87
	BOS	224,100	13,519	25.58
	RSR	39,660	1,864	4.53
	MHT	24,480	1,024	2.79
	EWB	2,485	262	0.28
ATCT/DF	ACK	67,707	9,185	7.73
ATCT/FDEP	BGR	64,440	1,688	7.36
ATCT/TTY	BDR	33,400	2,196	3.81
ATCT/TOWB	BVY	156,300	8,131	17.84
	LEB	160,680	7,357	18.34
	HFD	132,480	5,671	15.12
	DXR	159,360	6,924	18.19
	GON	111,000	3,889	12.67
FSS	BGR	60,720	2,391	6.93
	AUG	34,009	743	3.88
	AUG	34,788	1,061	3.91
	BOS	6,003	545	0.69
	BOS	111,047	7,164	12.68
	BOS	69,120	3,956	7.89

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
	BOS	562,000	31,217	64.16
	BOS	145,900	8,210	16.66
	MPV	52,170	1,515	5.76
GS	PQI	10,680	587	1.22
	MDC	23,977	1,800	2.74
	RTSR	32,970	2,114	3.76
	LEB	17,200	1,149	1.96
	MHT	13,360	647	1.53
	PVD	32,612	1,530	3.72
	HVN	5,609	422	0.64
	EEN	27,300	1,552	3.12
H	SRX	2,309	197	0.26
	SEW	21,328	1,249	2.43
	BTV	32,868	1,142	3.75
	VKN	5,990	328	0.68
	DRY	7,102	404	0.81
HH	TUK	55,700	4,475	6.36
	EGR	4,048	344	0.46
	BQI	15,880	855	1.81
	AQD	4,098	170	0.46
LOC	BHB	18,158	900	2.07
	ME	6,713	236	0.77
	PQI	13,320	714	1.52
	MDC	45,832	2,716	5.23
	RSR	63,835	3,818	7.29
	MPV	8,670	419	0.99
	MHT	20,945	917	2.39
	CON	12,352	607	1.41
	BDL	10,570	633	1.21
	HVN	27,051	1,725	3.09
	GON	42,277	1,855	4.83
	BDR	16,800	1,014	1.92
	EEN	13,068	659	1.49
	BAF	19,865	554	2.27
MALSR	BGR	7,244	511	0.83
	OCKL	825	66	0.09
	RSR	14,728	1,144	1.68
	MHT	11,770	932	1.34
	ARK	6,360	504	0.73
	BAF	16,664	758	1.90

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
	BDL	11,280	784	1.29
	PQI	6,541	396	0.75
	RKLD	7,087	466	0.81
MM	BGR	9,347	371	1.07
	PQI	4,919	302	0.56
	BED	17,126	1,259	1.96
	RSR	14,641	1,046	1.67
	BTV	16,810	695	1.92
	LEB	236	68	0.03
	PVD	1,021	89	0.12
	ACK	30,718	2,068	3.51
	PVD	6,196	465	0.71
	HYA	9,408	671	1.07
	BDL	17,139	775	1.96
	GON	79	32	0.01
	EEN	364	50	0.04
OM/LOM	BGR	21,830	936	2.49
	PQI	7,401	432	0.84
	PWM	6,754	394	0.77
	LIP	9,195	730	1.05
	BOS	13,492	923	1.54
	MDC	2,508	215	0.29
	BED	14,276	904	1.63
	RSR	7,316	561	0.84
	BTV	8,070	404	0.92
	ACK	9,356	645	1.07
	PVD	3,299	260	0.38
	EWB	4,768	367	0.54
	HYA	4,404	377	0.50
	BDL	6,813	564	0.78
OM	LEB	6,965	522	0.80
	MPV	320	131	0.04
	MHT	235	33	0.03
	EEN	424	59	0.05
RCAG	BGR	56,840	1,961	6.49
	ZBW	58,809	3,445	6.71
	AUG	84,440	2,264	9.64
	EWB	46,894	2,588	5.35
	BDL	10,920	559	1.25
	BDR	137,700	5,959	15.700

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
RMLR	QYD	80,840	3,034	9.23
	QYF	31,432	1,258	3.59
	QYE	47,670	1,681	5.44
	QYC	36,567	1,565	4.17
	QYB	59,725	2,374	6.82
	QYH	38,036	1,347	4.34
	QYK	48,399	2,364	5.53
	QYI	39,003	1,474	4.45
	QYI	42,983	1,474	4.91
	QBB	82,854	3,152	9.46
	QXF	40,752	1,802	4.65
	QBC	28,235	1,295	3.22
	QXD	28,314	1,106	3.23
	QXE	39,828	1,515	4.55
	QYL	45,725	2,040	5.22
	QYG	21,860	818	2.50
RTR	BGR	37,440	1,400	4.27
	MLT	35,216	1,548	4.02
	BOSA	200	44	0.02
	ORH	32,526	998	3.71
	MHT	7,042	358	0.80
	ASH	27,600	1,285	3.15
	CKA	17,516	1,754	2.00
	PVK	41,600	2,055	4.75
	MVY	11,944	857	1.39
	EWB	29,817	1,892	3.40
	HYA	39,154	1,215	4.47
	BDL	17,472	637	1.99
	BDR	13,596	799	1.55
VASI/LOC	BGR	17,093	910	1.95
	BGY	63,820	2,104	7.29
	PWM	19,280	661	2.20
	MHT	12,534	591	1.43
	BDL	30,618	1,358	3.50
	BDL	8,628	409	0.98
	BDL	4,800	231	0.55
VOR	MPV	67,200	1,751	7.67
VOR/DMER	HTR	134,520	5,643	15.36

Facility Type	Location	1977 Total Usage (kWh)	1977 Cost ($)	1977 Average Usage (kW)
VORTAC	BGR	175,560	4,786	20.04
	ENE	133,120	4,108	15.20
	BTV	121,700	3,170	13.89
	MHT	132,360	5,054	15.11
	CON	147,000	6,288	16.78
	PVD	155,820	6,117	17.79
	HFD	10,240	400	1.17
	CT	90,480	3,828	10.33
	CT	98,000	3,921	11.19
VORTAC/ LRCO	MLT	162,095	4,825	18.50
	ENE	133,120	4,108	15.20
	GDM	145,440	5,858	16.60
	BML	36,348	1,363	4.15
	LEB	56,400	2,844	6.44
	LWM	43,640	3,188	9.98
	ACK	101,644	12,162	11.60
	PUT	22,480	812	2.57
	MVY	9,312	690	1.06
	MVY	80,634	3,332	9.20
	HYA	135,080	5,856	15.42
	CTR	84,040	2,721	9.59
	GON	30,320	1,273	3.46
	BDR	62,880	2,605	7.18
	ORW	12,400	470	1.42
	EEN	112,600	4,390	12.85
	PQI	201,400	6,613	22.99
	PNN	42,989	1,872	4.91
		MISCELLANEOUS		
FM/H	MWX	15,580	641	1.78
FM	MPV	394	110	0.04
RCO	MLT	29,203	1,244	3.33
REIL	BED	310	51	0.00